# TECHNICAL AND ECONOMIC FEASIBILITY OF AN EARTHQUAKE WARNING SYSTEM IN CALIFORNIA

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# TECHNICAL AND ECONOMIC FEASIBILITY OF AN EARTHQUAKE WARNING SYSTEM IN CALIFORNIA

By

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Any errors or omissions in the final report are, of course, our own.

# Executive Summary

## Background

The Department of Conservation was directed to prepare a feasibility study of an earthquake warning system (EWS) for California, pursuant to Chapter 1492, Statutes of 1986, and the 1987 Budget Act. The study was to include (1) possible scenarios for seismic activity along the San Andreas fault north of the Los Angeles metropolitan area, (2) a description and evaluation of an EWS, (3) an assessment of the value of a warning, and (4) a description of the funding, management, reliability, and liability aspects of an EWS.

An EWS is not an earthquake prediction system. Rather, it would provide users with a warning that an earthquake has begun. Depending on the distance of the user from the earthquake epicenter, the warning could be received some seconds or tens of seconds prior to the onset of strong shaking.

The study area for this report includes those counties affected by earthquakes occurring along the San Andreas, San Jacinto, and Imperial faults in southern and central California and also the Silicon Valley (Alameda and Santa Clara counties).

## Method

An assessment of the value of an EWS is inherently difficult because (1) potential users are asked to identify uses for a nonexistent system, and (2) the estimated benefits and costs associated with an EWS are based on highly uncertain estimates of earthquake probability, site effects, and building damage.

In this study, potential uses of an EWS were identified by conducting three independent, but complementary, activities:

- a survey of 168 large private and public California organizations to estimate the benefits that an EWS would provide them in the case of a future large earthquake,
- a survey of 78 small California manufacturers who had recently experienced a damaging earthquake to determine whether they could identify uses for an EWS, based on their recent experience, and
- an expert review of the uses of an EWS to industrial facilities, based on 82 observations of earthquake damage to such facilities during 17 recent worldwide earthquakes.

## Findings

- For earthquakes of M7 and less, average warning times of 10 seconds or less could be provided in the significantly damaged areas (Modified Mercalli Intensity VIII or greater). For an earthquake of about M7.5 or greater, an average warning time of approximately 30 seconds could be provided in the significantly damaged areas.

- Based on the results from two surveys, potential users generally desire warning times of 30 seconds or greater. Thus, candidate earthquakes for an EWS should be M7.5 or greater events. In southern California, earthquakes of M7.5 or greater would be limited, in all likelihood, to the southern San Andreas fault. The U.S. Geological Survey estimates that the annual probability of such an event is about 2 percent.

- An EWS is technically feasible and could be built for $3.3 million to $5.8 million in capital costs with annual operating costs of $1.6 million to $2.4 million. depending on the ultimate configuration of the system

- The EWS, to be cost-beneficial, must provide outstanding benefits (estimated savings) to potential users, in the range of tens to hundreds of millions of dollars. Given a 2 percent annual probability of earthquake occurrence and a 20 to 100 percent annual probability of a false alarm, the estimated savings from an EWS must be at least 50 times the annual system costs *plus* 10 to 50 times the cost of a false alarm.

- There appears to be little chance of receiving State or Federal funding for a California EWS. It is improbable that private venture capital financing would be available, based on the financial risk and uncertain returns that we have observed.

- The liability considerations of a State EWS appear to be addressable by contractual arrangements and the enactment of clarifying legislation.

## Conclusions

In order for an EWS to be cost-beneficial, it would have to provide benefits of tens to hundreds of millions of dollars upon the occurrence of a warnable earthquake. Based on our review, there is no compelling evidence that an EWS in California would produce such large benefits. It would not be, therefore, justifiable, on a cost-benefit basis, to construct an EWS at this time.

# Chapter One–Introduction

## Authority

Chapter 1492, Statutes of 1986 (SB 1238–see Appendix A), specifies that the Department of Conservation, in consultation with the Seismic Safety Commission, undertake a feasibility study of an earthquake warning system (EWS) for California. The study is to include the following:

1. Possible scenarios for seismic activity along the San Andreas fault north of the Los Angeles metropolitan area;

2. Description of the development, use and transmission of a warning signal;

3. Evaluation of the technical and economic feasibility of implementing the early warning system;

4. Assessment of the value of warnings to various specified elements of society; and

5. Description of funding, management, reliability and liability aspects of the system.

Funding for the 18-month study was made available on July 1, 1987 in the 1987 Budget Act (Chapter 135, Statutes of 1987). Subsequently, a study team consisting of a senior seismologist, an associate seismologist and a policy and economic analyst was assembled to undertake the study.

## Background

The purpose of an earthquake warning system is to provide its users some seconds or tens of seconds of warning prior to the onset of strong and potentially damaging ground motion. In principle, an EWS could provide warning of an earthquake in progress along the San Andreas fault, or other hazardous faults in California, by taking advantage of the difference in the velocity of seismic waves and that of radio waves. Japanese Railways (JR) operates such a system. The JR system reduces the speed of or stops the *shinkansen* ("bullet train") and conventional trains whenever a predetermined level of ground motion is exceeded along a portion of the track. Our review of the JR earthquake warning system is included in Appendix B. This study concentrates on the design, uses, costs, benefits, and liability considerations if an EWS were to be operated in California.

## Scope

A primary study area was chosen that includes 15 southern California counties that would be affected by damaging motion from earthquakes along southern California faults, including (among others) the southern San Andreas, San Jacinto and Imperial faults. We chose to limit our study to this part of southern California because (1) Chapter 1492 specified that the study evaluate the effectiveness of an earthquake warning system to detect activity *along the San Andreas fault* north of the Los Angeles metropolitan area, (2) most researchers believe that the southern San Andreas fault (southern Monterey County and below) is more likely to generate a major earthquake in the near future than the northern end, and (3) a report focusing on a specific region of the state should provide information which can be generalized to any part of the state. The primary study area includes Fresno, Imperial, Kern, Kings, Los Angeles, Monterey, Orange, Riverside, San Benito, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Tulare, and Ventura counties. This area is a 73,448 square mile region with an estimated 18.5 million inhabitants, or 66 percent of the state's population.

In our study, we used the categories of potential users of an EWS that were specified by the original legislation authorizing this project (Chapter 1492). They include public officials, schools, hospitals, police, fire stations, private industry, critical defense contractors and gas, oil and electrical industries. In order to collect information on the potential uses of an EWS, we chose to survey these user groups in the primary study area. In addition, we conducted surveys of (1) a limited number of large computer-related manufacturing firms in the Silicon Valley (southern Alameda and Santa Clara counties); and (2) 78 small manufacturing firms located within 10 miles of the October 1987 Whittier earthquake.

We also conducted other data gathering activities, including: (1) consulting a proprietary database of earthquake damage data of 82 major industrial facilities worldwide; and (2) meeting with personnel of Japan Railways' Railway Technical Research Institute and observing the earthquake warning system for the *shinkansen* and conventional train lines.

## Organization of the Report

This report is written for use by decision makers and therefore an attempt was made to omit from the main body technical jargon and data that is not directly useful in presenting our findings. More detailed and technical information is provided in the appendices.

Chapter Two outlines seismic hazards in southern California, including data on earthquake faults in southern California, earthquake damage, and earthquake probabilities.

Chapter Three describes the data collection activities undertaken in this report. The chapter includes the methodology, response, and results from two surveys. This chapter also reviews and analyzes data from an earthquake damage database.

Chapter Four discusses the seismological and user constraints on the performance of an EWS. The possible warning times available from postulated earthquakes together with the user's desired warning times are evaluated for their relevance in designing the EWS. The chapter also includes various warning system configurations and cost estimates.

Chapter Five describes two possible warning systems that could be implemented within the Los Angeles Basin, including system cost estimates, analysis, and conclusions.

Chapter Six includes an economic evaluation of the EWS. The chapter includes a decision analysis framework that outlines the economic and systemic parameters under which an EWS must operate to be cost-beneficial. In addition, we discuss the ability of an EWS to reduce casualties.

Chapter Seven outlines the funding and management issues associated with an EWS. The chapter describes public and private operations and possible funding sources for an EWS.

Chapter Eight discusses the liability issues of an EWS. Current California law regarding earthquake warning and liability is discussed.

Chapter Nine presents the conclusions, options and our recommendations. A bibliography and appendices follow.

# Chapter Two—Southern California Earthquake Hazard

The feasibility of an earthquake warning system in California is dependent both on user-related and earthquake fault-related factors. In this chapter, we discuss the latter. We present this discussion here in order to introduce the seismic hazard of southern California, as well as present the necessary technical background for specifying a system design.

To assess the feasibility of an earthquake warning system for any geographical area, the regional seismic hazard/risk must be understood. In this chapter, we discuss aspects of the seismic hazard in southern California. This discussion is geared (as much as possible) toward the non-scientist to provide a foundation for the considerations that follow.

The assessment of seismic hazard presented here is based on the incorporation of historic and prehistoric earthquake occurrence data with specific earthquake recurrence models. Namely, evidence suggests that a given section of a fault may rupture with earthquakes of similar magnitude at approximately evenly-spaced intervals. To the extent that this model is incorrect (and Professor Kerry Sieh of California Institute of Technology (Caltech) has presented data that suggests that, over thousands of years, the particular model is not completely accurate), the hazard assessment is more uncertain.

For brevity, we will use the following naming conventions:

- g (after a number) is a unit of acceleration, a measure of ground motion (1.0g ≈ 980 centimeters per second-squared).
- km designates kilometers (1 km= 0.62 mile).
- M(and a number) designates the magnitude of an earthquake. For example, M7 represents an earthquake with a magnitude of 7.
- P-waves are the compressional (sound) waves which travel at a velocity of 5.0-6.5 km per second (2.7-3.5 miles per second) in the earth's crust.
- S-waves (shear waves) travel at a velocity of 3-3.7 km per second (1.7-2.2 miles per second).

### Earthquake Faults in Southern California

Southern California has numerous faults capable of generating damaging earthquakes. Indeed, it is probable that many hazardous faults have yet to be discovered and mapped. Figure 2.1 shows the location of some of the major faults of southern California relative to the major metropolitan areas of Los Angeles, Orange, San Diego, San Bernardino and Riverside counties. Any of these faults could generate a damaging (approximately M6.0 or greater) earthquake at any time. Earthquakes that have occurred since 1925 and that were M5.9 or larger are also plotted in Figure 2.1. Since 1925, there have been only three M7 or greater earthquakes in the study area.

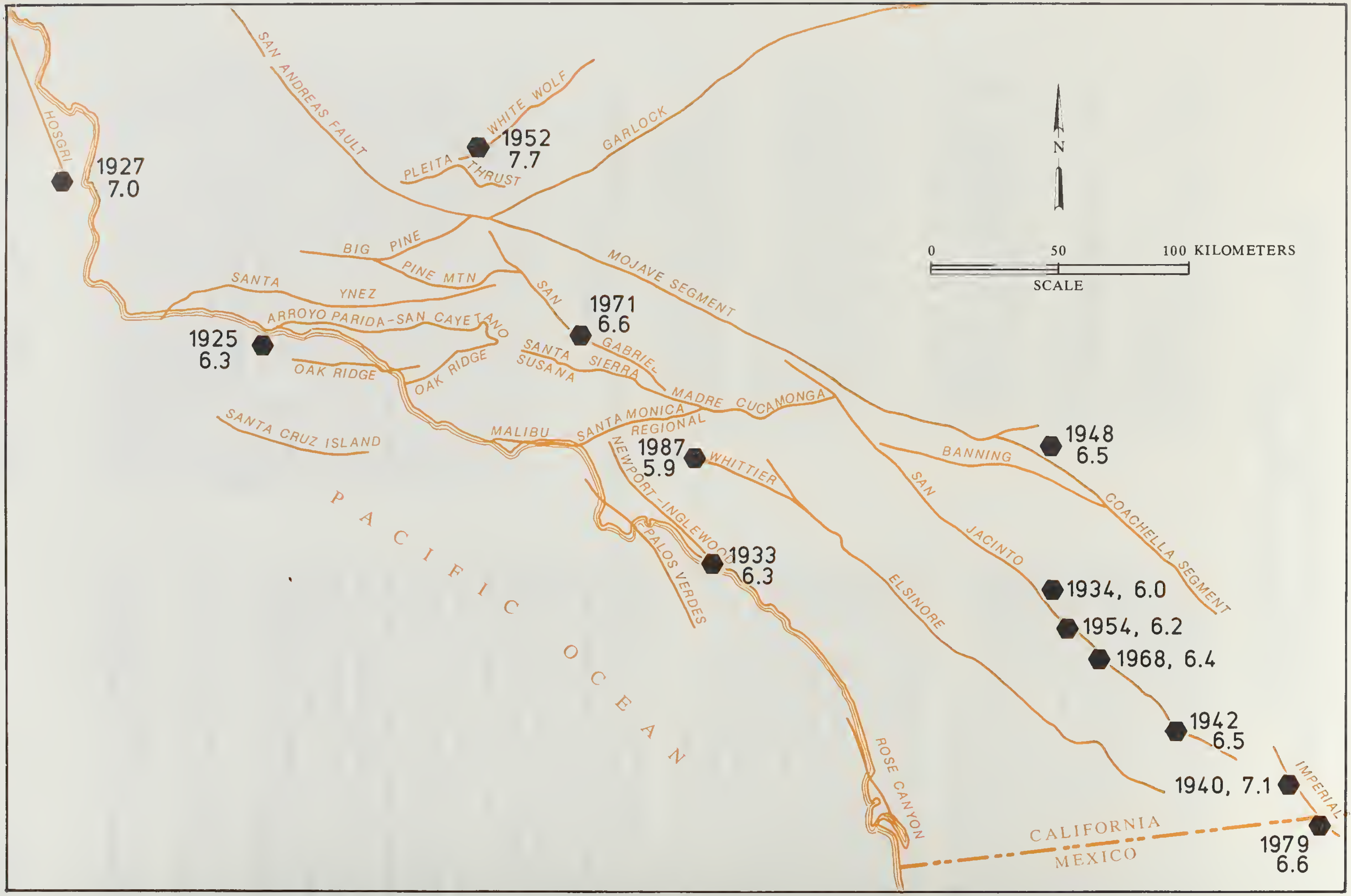



Figure 2.1 Major Quaternary faults in Southern California and historical M≥ 5.9 earthquakes since 1925.

These are the 1927 Lompoc (M7.0), the 1940 El Centro (M7.1) and the 1952Tehachapi (M7.2) earthquakes. None have occurred within the larger metropolitan areas.

**San Andreas Fault**

Among the "quietest" faults during the time period covered in Figure 2.1 is the San Andreas fault. Only one major earthquake has occurred along its entire length in southern California (from southern Monterey County in the north to the Salton Sea in the south) since the early 19th century. This was the great Fort Tejon earthquake of 1857, estimated M8.3. The fault ruptured from Parkfield in southern Monterey County to Cajon Pass near San Bernardino. When one speaks of "the big one" for southern California, it is a repeat of this event. Yet, a repeat of the 1857 earthquake may not be the most likely M7 or greater event in the near future. Professor Sieh has excavated the San Andreas fault in a number of locations. He concludes that:

- The section of the fault northwest of Gorman has ruptured less frequently than that between Gorman and Cajon Pass (known as the Mojave segment).

- The Mojave segment has had an earthquake every 145 years or so, since about 1000 A.D.

- The most recent known large earthquake to occur along the Coachella Valley section was in about 1680 A.D. This section of the fault has not had any historical seismic activity of significance. If earthquake repeat times on this segment are about a few hundred years, a large earthquake could be expected there in the relatively near future.

Thus, based on current understanding, the two segments of the San Andreas fault most likely to have a major (e.g., M7.5) earthquake in the near future are the Mojave and the Coachella sections. The section of the San Andreas fault between the Mojave and the Coachella Valley segments is very complex. Its seismic history and potential are not well understood. It is possible that all three sections could rupture in one great earthquake with a magnitude of about M7.8. The likelihood of this larger event is unknown.

**Other Faults**

Other faults in southern California have not been so well studied. Although knowledge of the seismic history/prehistory is incomplete, the general hazard can be discussed. A number of scientists have compiled data on various faults, emphasizing the anticipated magnitude and recurrence intervals of earthquakes. Estimates of earthquake probability,however, require knowing the times of previous events. For most faults, this information is not yet available. Thus, our knowledge of the seismic hazard is incomplete, at best. Of the faults shown in Figure 2.1, only a few have generated significant earthquakes in this century.

The 1933 Long Beach (M6.3, Newport-Inglewood fault), 1971 San Fernando (M6.5, "San Fernando" fault) and 1987 Whittier Narrows (M5.9, unidentified fault) are examples of earthquakes that could occur along any of the area's faults at any time. The generally accepted judgment (see, for example, Ziony and Yerkes, 1985) is that credible earthquakes for most of the faults shown in Figure 2.1, except the San Andreas and San Jacinto faults, are in the M6.5 to M7 range. Credible earthquakes for the San Jacinto fault and the San Andreas fault (see above) are M7 and M8, respectively.

While this discussion concentrates on known faults, it is possible, if not likely, that the next damaging earthquake in the Los Angeles area will occur on an entirely unknown fault. Indeed, the fault source of the 1987 Whittier Narrows earthquake (M5.9), apparently buried beneath the sediments of the Los Angeles Basin, has still not been accurately located. Some scientists speculate that such a buried fault, if it underlies a large portion of the basin, could generate a major earthquake and cause significant damage in the Los Angeles area.

### Earthquakes and Damage

In order to evaluate the potential advantages of an earthquake warning system, we must be able to estimate, at least roughly, the extent of damage that may result from future earthquakes. The damage caused by an earthquake is a function of its magnitude, the proximity of the earthquake rupture to populated areas and the local geological substrata. The damage is also related to a facility's construction type and quality. For earthquakes in the magnitude 6 to 7 range, we can draw on a number of studies of historical California earthquakes. Larger events, however, are much less numerous. Most occurred before the advent of high-rise buildings in California.

Figures 2.2a-d show examples of the extent of earthquake damage in California for a variety of earthquake magnitudes. The contours are of Modified Mercalli Intensity, a measure of the earthquake's effects, rather than of its "size." The descriptions for the various intensity levels are listed in Appendix C. Intensity VI (contours not shown) is considered to be the threshold of minor damage. Intensity VII and greater (inside the solid contour lines in Figures 2.2a-d) include areas of moderate to severe damage. Areas of Intensity VIII and greater are stippled in the figures. For example, Coalinga suffered intensity VIII in the 1983 earthquake. Older unreinforced masonry buildings and wood homes not tied to their foundations were severely damaged but modern buildings suffered relatively little damage. Although an earthquake warning system will not mitigate severe building damage or collapse, we believe that intensity VIII is the level at which a warning could become helpful in mitigating damage.

Thus, of primary concern to this study is the distance from an earthquake epicenter to the limits of intensity VIII or greater damage. Figure 2.3 is a plot of distance, from an epicenter to the furthest intensity VIII, versus magnitude, for a number of historical California earthquakes. Most of the data are for M6 to M7 earthquakes, the most common damaging earthquakes in California. These earthquakes generated intensity VIII damages at distances of up to 50 km from the earthquake epicenter. The two larger earthquakes in Figure 2.3 are the 1952 Kern County (M7.7) and the 1906 San Francisco (about M8.3). For these two earthquakes, intensity VIII damage extended about 80 and 370 km, respectively. The other two known

Figure 2.2a

1868 Hayward Earthquake, M6.8

LOCATION OF EPICENTERS


Figure 2.2b

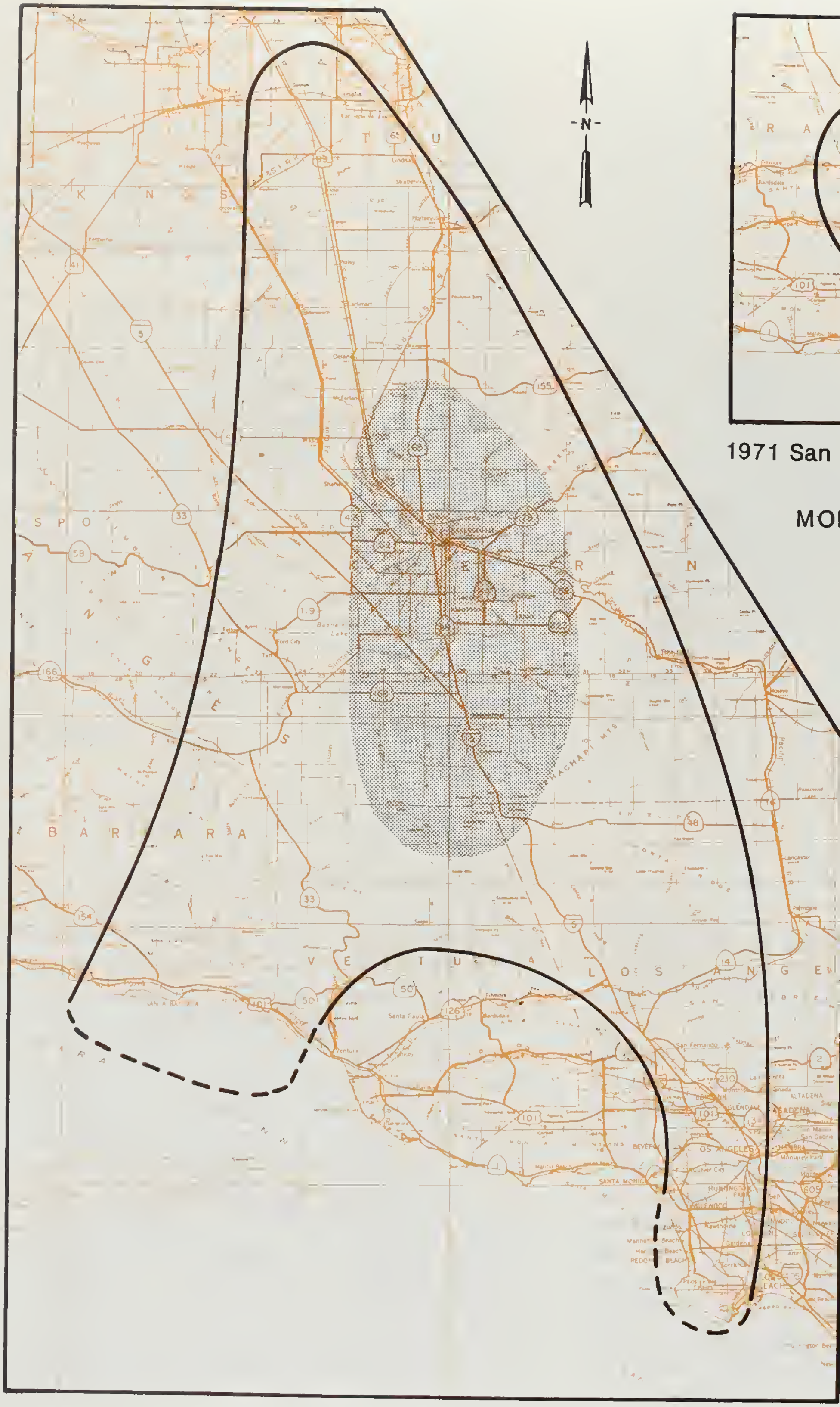
1983 Coalinga Earthquake, M6.7

MODIFIED MERCALLI INTENSITY


SCALE


Figure 2.2 Areas of Modified Mercalli Intensity VII and VIII and greater for selected historic California earthquakes.

Figure 2.2c



1952 Tehachapi Earthquake, M7.7

Figure 2.2d

1971 San Fernando Earthquake, M6.5

MODIFIED MERCALLI INTENSITY

VII or greater

VIII or greater

SCALE

0 40 Kilometers

LOCATION OF EPICENTER


Figure 2.2 Areas of Modified Mercalli Intensity VII and VIII and greater for selected historic California earthquakes.

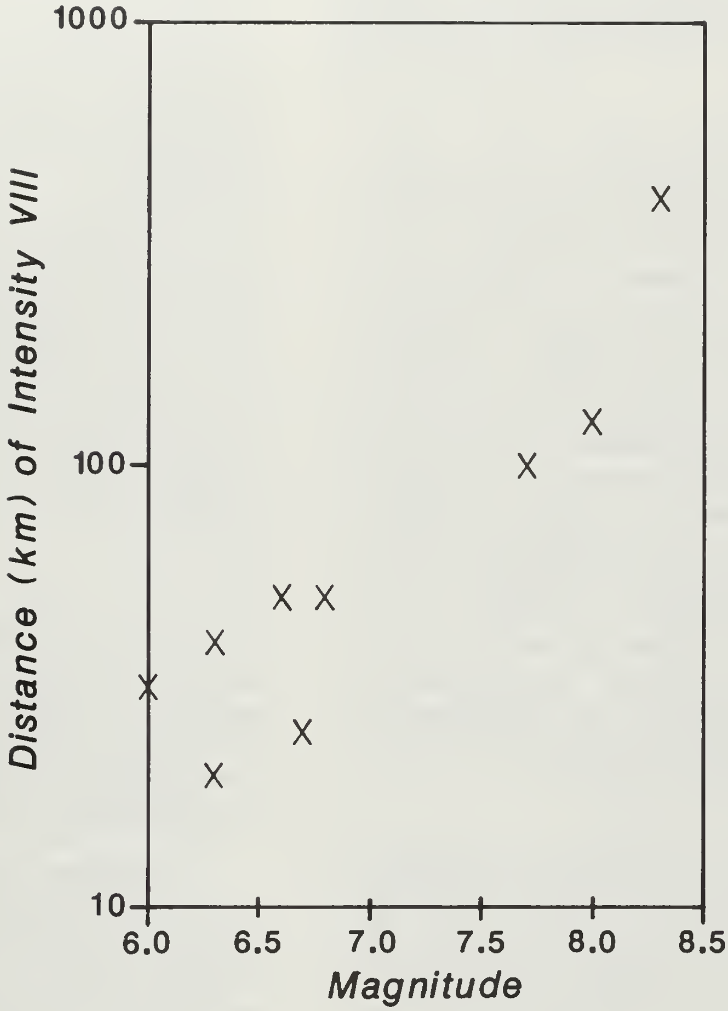



Figure 2.3 Distance from earthquake epicenter to limits of Intensity VIII damage.

historical California earthquakes with M8 or greater (1857 and 1872) are not shown on this figure. These older events are problematic, at any rate, because damage to the older construction types are not necessarily indicative of damage to modern construction.

We note that the larger magnitude earthquakes, M7 or greater, are rich in low frequency energy. The Modified Mercalli Intensity scale, however, is based on damage to structures that respond to (or resonate at) high frequency vibration. The 1952 Kern County earthquake did cause some nonstructural damage to high-rise buildings in downtown Los Angeles and the 1985 Mexican earthquake caused extensive damage in Mexico City, 350 km (219 miles) away, as a result of low frequency shaking. While no one expects a "Mexico City phenomenon" following the next M8.0 in Southern California, experience with California structures is insufficient to forecast the extent of damage produced by low frequency energy.

Low frequency motions notwithstanding, Figure 2.3 is indicative of the kinds of distances for which an earthquake warning system might be useful. For a M6-M7 earthquake, damage beyond about 20-100 km from the epicenter is probably not great enough to warrant a sophisticated warning system. For M7 or greater earthquakes, the intensity VIII area could extend along the fault for 100 to 400 km (from the epicenter), and away from (perpendicular to) the fault for up to 80 km. At these distances, warning times may be great enough to warrant such a system.

## Earthquake Probabilities

As the scientific community better understands the way faults behave and the history and prehistory of seismic activity in California, evaluations of the likelihood of earthquake activity in the near future improve. The probability of significant activity on a fault within a given time period is a function of the magnitude of the "typical" or "characteristic" earthquake for that fault (i.e., the amount of slip per event), the time between "typical" earthquakes and the amount of time since the last one. The U.S. Geological Survey (USGS) has recently reassessed earthquake probabilities for California for the next 30 years for the San Andreas and adjacent faults. They estimate the probability of a M7.5 or greater earthquake on the southern San Andreas fault to be 60 percent during the next 30 years, with the Coachella Valley segment (see discussion, above) having the highest single probability, 40 percent. Thus, there is a significant likelihood of major activity along the San Andreas fault during the lifetime of an earthquake warning system.

The San Andreas fault, however, is not the only hazardous fault in southern California. Any of the faults shown in Figure 2.1, and probably a number that are not, are capable of generating damaging earthquakes of M6.0 or greater. Unfortunately, not enough is known of the earthquake history of these faults to estimate the probability of future activity. Many of these faults have relatively slow rates of motion and, therefore, long times (on the order of thousands of years) between earthquakes. Nevertheless, all should be considered capable of generating M6 to M7 and greater earthquakes at any time.

Two recent earthquakes dramatically illustrated that faults that rupture on the surface are not the only ones that are hazardous. Neither the 1983 Coalinga (M6.7) nor the 1987 Whittier Narrows (M5.9) earthquake was accompanied by surface faulting. In the case of Coalinga, the general zone of buried faulting has been identified. However, the fault that generated the Whittier Narrows earthquake has not been located. It has been suggested that the entire Los Angeles Basin sits on top of a very large, buried fault. If this is the case, and if the potential magnitude of earthquakes on this fault is large enough to warrant consideration for a warning system, the need for a region-wide system, rather than one concentrating on specific faults, would be indicated.

## Summary

Decisions on the usefulness or feasibility of an EWS need to include all aspects of a region's seismic exposure. Factors to be incorporated include the faults contributing to the seismic risk, the expected magnitude of earthquakes along those faults, the probability of those earthquakes occurring and the severity and extent of the damage the earthquakes will inflict. For example, there is a 60 percent probability of a M7 or greater earthquake along the southern San Andreas fault within the next 30 years. Earthquakes of this magnitude generally inflict significant damage (intensity VIII or greater) at approximately 50 km (or greater) from the earthquake epicenter.

In southern California, however, there are numerous known faults–and probably several yet unidentified–that contribute to the region's seismic hazard. Unfortunately, for most of those faults, the factors listed above cannot all be accurately estimated at this time. Decisions on a warning system must take into account the fact that the region's entire seismic hazard is not completely known and cannot be entirely addressed.

# Chapter Three–EWS Uses Data Collection

Chapter 1492 specifies that this feasibility study include the:

"(3) Technical and economic feasibility of implementing the early warning system. Possible applications include automated shutdown of pipelines, transportation systems, computer systems, and other vital lifelines which would be damaged in an earthquake.

"(4) Assessment of the value of warnings to various elements of society, including public officials, schools, hospitals, police, fire stations, private industry, critical defense contractors, and gas, oil, and electrical industries. The assessment should include an estimate of the value of a warning as a function of the warning time and its reliability."

Because the effectiveness of an EWS depends on the acceptance of and participation in the system by users, we have attempted to make the feasibility study as "user-driven" as possible. That is, determination of respondents' desires and interests has preceded design, in an effort to tailor the system to the needs of the users.

To do this, we collected data from three sources:

- a survey of 164 large organizations in a 15-county study area and four large, computer-related manufacturing firms in the Silicon Valley (Santa Clara and Alameda counties),
- a survey of 78 small- to medium-size (10 to 250 employees) manufacturing firms located within 10 miles of Whittier, the site of the October 1987 earthquake, and
- a review and analysis of a earthquake damage database based on records from recent worldwide earthquakes.

The surveys were intended to collect information from potential EWS users on their earthquake risk, specific facility characteristics, and the applicability of an EWS to various facility operations. (Details of the survey materials, methods and results are presented in Appendices D, E and F.)

In the surveys of large organizations, we queried in-house earthquake experts to collect the organization-specific data on potential uses of an EWS. An expert survey approach depends on the objective, knowledgeable, and reasoned judgment of personnel familiar with their facility's operations rather than on the subjective and immediate responses given in public opinion polls. The surveys were directed to those personnel identified by each organization as best qualified to respond to our survey, including engineers, emergency responders, safety officers, and risk managers.

The survey of small manufacturing businesses near Whittier included personal interviews with owners and plant managers. As with the survey of large organizations, the respondents are presumedly most familiar with their operations. In addition, because these facilities were affected by the 1987 Whittier earthquake, the respondents should be sensitive to the vulnerable areas and operations within each facility.

We selected the survey method because of its advantages in collecting facility-specific data and because individual users will ultimately determine the worthiness of an EWS through their use or neglect of earthquake warning information. At the same time, a survey may not reflect the worth of an EWS because it may be difficult for respondents to fully appreciate the uses of a nonexistent system. In addition, the respondents' estimates of the system's value to their facilities–the savings and false alarm costs–are necessarily based on highly uncertain and speculative scenarios of earthquake damage. Thus, the survey results must be analyzed in view of these possible variabilities.

The review and analysis of earthquake experience data provides a comparison between (1) postulated damage and the potential uses of an EWS provided in the surveys, and (2) an expert analysis of actual earthquake damage and the implications for an EWS.

### Survey of Large Organizations

Chapter 1492 specifies the potential users and applications of an EWS that are to be evaluated. In addition, prior to initiating a survey effort, we asked representatives of various State agencies to identify other potential users/uses of an EWS. The potential users/uses resulting from this process and the requirements of Chapter 1492 provided project staff with a variety of potential users/uses for an earthquake warning system. These ideas were used to draw a sample for the survey. The sample of potential users was selected based on the location and relative size of organizations within the user groups.

The sample was drawn from the study area including 15 counties of southern and central California: Fresno, Imperial, Kern, Kings, Los Angeles, Monterey, Orange, Riverside, San Benito, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Tulare, and Ventura. This study area includes all counties likely to be affected by strong ground motion from a major earthquake on the southern San Andreas fault.

The sample also drew from the most important participants in each user group, based on their relative size within the group. In general, schools with the greatest enrollment, hospitals with the largest number of licensed bed-days, and manufacturers with the largest revenues were selected. We chose to sample "large" users because large organizations are likely to:

- experience a larger economic impact resulting from earthquake damage,
- have the in-house expertise to respond to the survey,
- have systems or equipment that could respond to a warning, and
- have the financial wherewithal to subscribe to an EWS.

When it was necessary to balance the geographic representation of the sample, the users in a group were selected on the basis of location as well as their relative size.

In addition to the 15-county study area, a limited survey of high technology firms in the Silicon Valley was conducted. The purpose of the narrower study was to determine whether the unique manufacturing conditions found in the Silicon Valley would support the use of an EWS. While the larger survey effort focussed on various uses in a 15-county region, this effort polled only industrial facilities typical of the Silicon Valley. Thus, other potential users such as fire and police services, public utilities, and the like were not surveyed in the Silicon Valley. The survey instrument and methodology, however, were identical to the larger survey in every other aspect.

The 15-county sample includes 164 potential users of various types, 132 of types specified by Chapter 1492 and 32 others. The Silicon Valley survey includes four computer-related organizations. The results of both surveys are reported together in Table 3.1 and in the results below.

The survey was administered by:

- calling potential users by telephone to request their participation in the survey,
- mailing a survey package to potential users,
- making follow-up telephone contacts, and
- conducting personal interviews with a portion of the participants.

**Survey Responses**

As shown in Table 3.1, 80 (48 percent) of the 168 potential users contacted had returned 121 surveys. Of the 121 surveys, eight surveys were completed for facilities that were either not within the study area or did not describe specific facilities. The geographic locations of study area facilities identified by the respondents are shown in Figure 3.1.

**Use for Earthquake Warning**

Forty-four (36 percent) of the 121 surveys returned indicated 82 separate uses for an earthquake warning between 1 and 120 seconds. Thus, many respondents indicated more than one use for an EWS. The 82 separate uses identified by these responses may be grouped according to four categories (see Appendix G for a complete listing of these uses by category and warning time):

- *Computer* uses include the shutdown of computer systems and disk drives or switching to emergency power.
- *Facility* applications include switching plant site power or natural gas and opening doors to remove fire fighting equipment prior to strong ground shaking. This category also includes the automatic disconnection of power to railroad lines, thereby stopping trains.
- *Personnel* responses range from evacuating buildings to activating employee response plans. Often these responses were not specific as to the actual personnel-related use of the EWS.

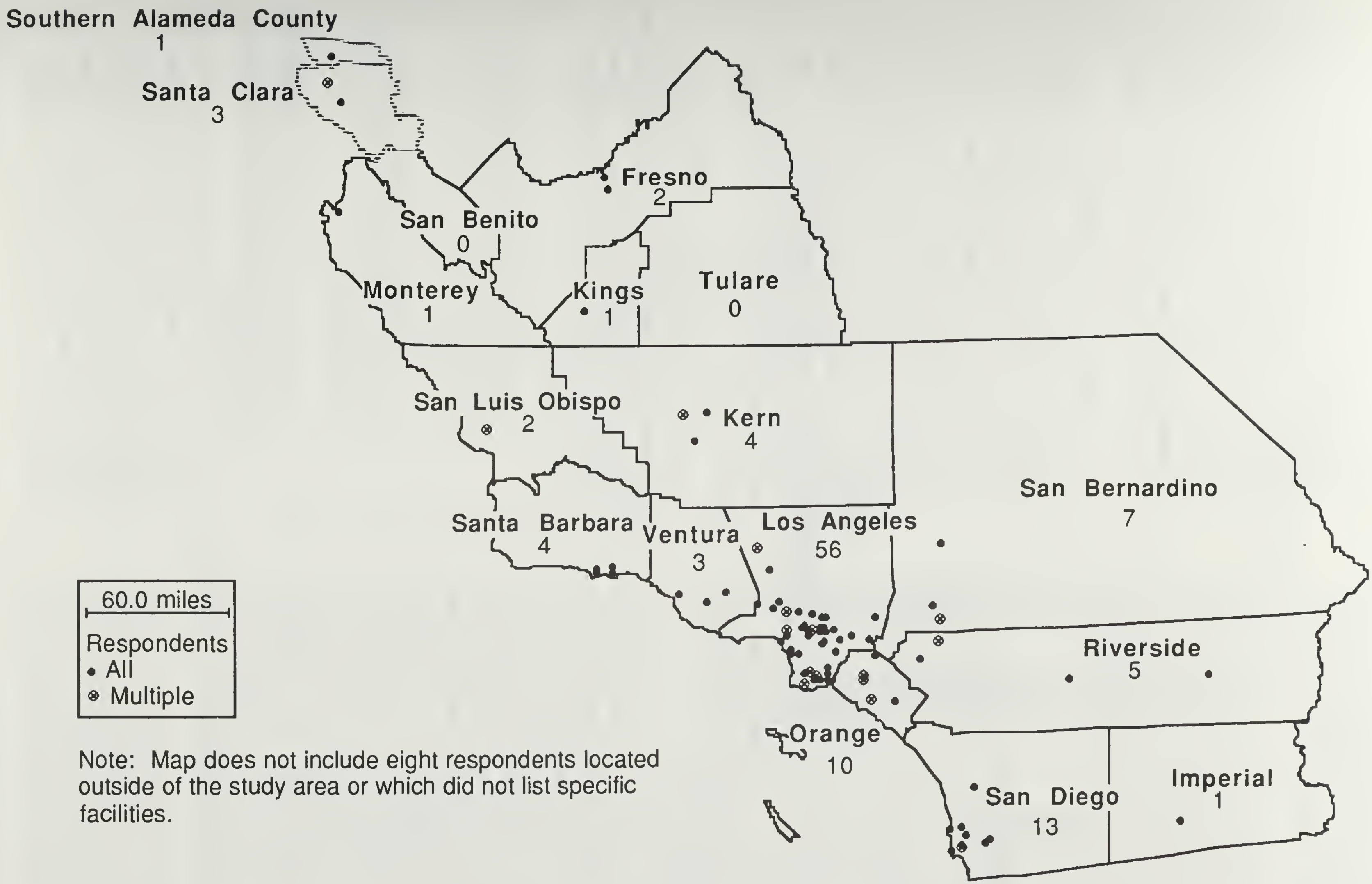
- *Production* applications include diverting arriving aircraft, securing large animals, the shutdown of pipeline transfer operations and the controlled shutdown of test equipment and various production processes.

As shown in Figure 3.2, the majority of uses in each category, according to respondents, require between 60 and 120 seconds to effect mitigating action. The mean and median warning times indicated were 72 and 60 seconds, respectively. The survey results indicate that 70 percent of the EWS users said they require at least 60 seconds of warning, 74 percent more than 30 seconds. Thus, only about 26 percent of the EWS users desire warnings of 30 seconds or less.

**Table 3.1**

**Sample of Potential Users and Survey Response, by Legislative Requirement and Business Type**

| **Potential Users/Uses Specified by Chapter 1492** | **Number Sampled** | **Number Responses** | **Percent Responding** |
|---|---|---|---|
| Computer Systems | 2 | 1 | 50 |
| Defense-Related Industry | 7 | 2 | 29 |
| Gas, Oil, & Electrical Industries | 21 | 13 | 62 |
| Hospitals | 7 | 2 | 29 |
| Other Vital Lifelines | 17 | 12 | 71 |
| Pipelines | 3 | 0 | 0 |
| Police & Fire Services (includes emergency services) | 21 | 11 | 52 |
| Private Industry (manufacturing) | 15 | 6 | 40 |
| Public Officials | 11 | 5 | 45 |
| Schools | 8 | 7 | 88 |
| Transportation Systems | 20 | 7 | 40 |
| Subtotal | 132 | 66 | 50 |
| **Other Potential Users/Uses** | | | |
| Banking and Finance | 9 | 3 | 33 |
| Insurance | 5 | 0 | 0 |
| Recreation/Entertainment Industries | 4 | 1 | 25 |
| Various Others | 14 | 6 | 43 |
| Subtotal | 32 | 10 | 31 |
| **Silicon Valley Applications** | | | |
| Computer-Related Manufacturing | 4 | 4 | 100 |
| Totals | 168 | 80 | 48 |




Note: Map does not include eight respondents located outside of the study area or which did not list specific facilities.

Figure 3.1 Earthquake Warning System Study. Survey results from 121 respondents in a 15-county region plus Silicon Valley counties (Alameda and Santa Clara).

In effect, the uses are clustered around the half minute, one minute and two minute levels of warning time.

The uses of the EWS were varied. The predominant (39 percent) applications are for production-related processes and activities. Another 23 percent are for the personnel uses for an EWS while computers and facilities were cited for 20 and 18 percent, respectively.

In general, all EWS uses were represented among the various warning times. Personnel applications, however, were *least* represented among uses with warning times of 30 seconds or less, reflecting the time needed to evacuate building areas. Computer and production applications represent nearly two-thirds of the responses for short warning times (30 seconds or less), perhaps reflecting the availability and use of switching equipment to effect action.

*Long Warning Times (60-120 seconds).* Although it is possible to conceive of uses for warning that take short amounts of time (10 seconds or less), very few respondents indicated a use or desire for such short times. We believe that there are at least three reasons for respondents to desire longer warning times. First, many respondents appear to be reluctant to delegate a shutdown decision to automated equipment, thereby removing humans from the decision process. In some cases, a false alarm could be extremely costly–and dangerous–to potential users.

Second, major facilities contain large equipment and systems that are not easily or quickly shut down. For example, large valves used in gas, oil, and water delivery systems frequently take minutes to open or close. Thus, the minimum times to take action on such systems are likely to be long. In addition, although an earthquake warning could initiate (if not complete) a damage mitigation process for major systems prior to strong shaking, potential users may wish to confirm the event before mitigating action is taken.

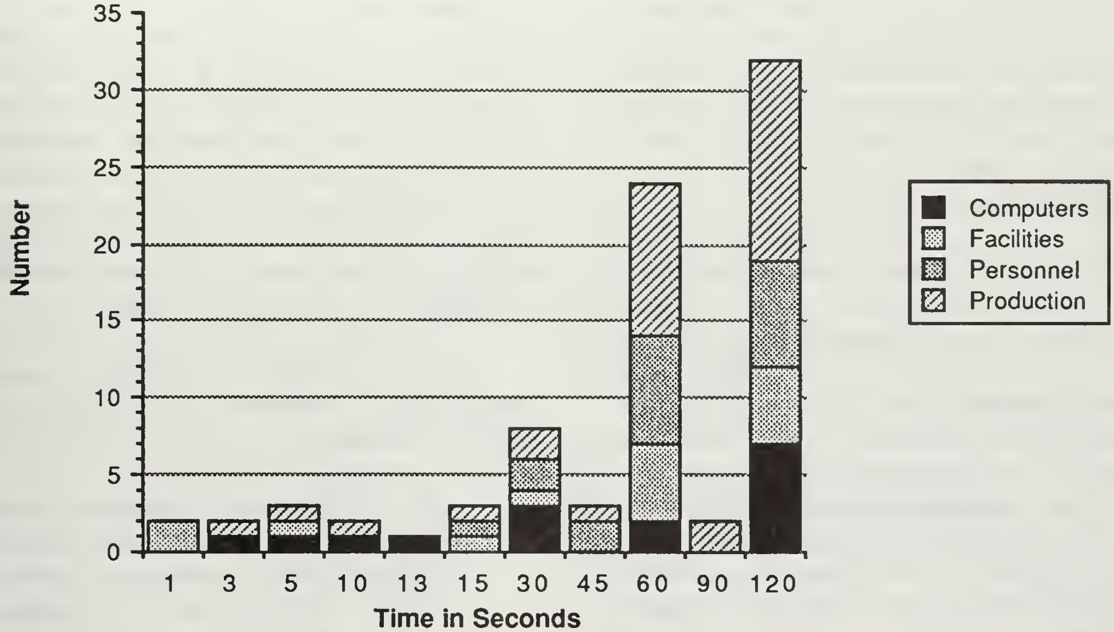
Finally, the personnel uses for warning given by respondents generally included evacuation of buildings, which requires relatively long warning times. An earthquake warning system, however, could not guarantee sufficient time to effect such action. We note that there are other personnel response actions such as crawling under a desk or getting away from windows which require only a few seconds and could therefore be implemented with only a short warning.

*Short Warning Times (1-30 seconds).* As indicated in Figure 3.2, 21 uses (26 percent) required warning times of 30 seconds or less. Three interesting uses for a short earthquake warning were:

- diverting arriving aircraft by airport ground control (3 seconds),
- automatically disconnecting the power from railroad lines (15 seconds), and
- shutting down a fire department's computer-aided dispatch system (30 seconds).

Other uses ranged from personnel response to computer-related and facility operations actions. Some of these uses, however, may have limited utility. For example, two uses involve disengaging the natural gas and

## Figure 3.2
## Types of Uses and Desired Warning Times
## Survey of Large Organizations




| Times | Computers | Facilities | Personnel | Production | Totals | Percent |
|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 0 | 0 | 2 | 2 |
| 3 | 1 | 0 | 0 | 1 | 2 | 2 |
| 5 | 1 | 1 | 0 | 1 | 3 | 4 |
| 10 | 1 | 0 | 0 | 1 | 2 | 2 |
| 13 | 1 | 0 | 0 | 0 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 3 | 4 |
| 30 | 3 | 1 | 2 | 2 | 8 | 10 |
| 45 | 0 | 0 | 2 | 1 | 3 | 4 |
| 60 | 2 | 5 | 7 | 10 | 24 | 29 |
| 90 | 0 | 0 | 0 | 2 | 2 | 2 |
| 120 | 7 | 5 | 7 | 13 | 32 | 39 |
| | | | | | | |
| Totals | 16 | 15 | 19 | 32 | 82 | 100 |
| Percentage | 20 | 18 | 23 | 39 | 100 | |

* Percent totals may not sum due to rounding.

electrical power supply at a manufacturing facility if given one second of warning. The respondent estimates that a major conflagration may be averted by taking these actions. If in fact only one second is necessary to effect these actions, a local on-site trigger may be more effective. Other short warning time uses that are of dubious benefit include shutting down personal computers and energy management systems.

**Savings and False Alarms Costs**

The survey respondents were asked to estimate the saving (or avoided losses) that an earthquake warning might provide to their facility. In addition, respondents were asked to identify the consequences and estimate the costs of a false earthquake warning (EWS issues a warning, but no damaging earthquake occurs). These results only reflect those responses that indicated a use for a warning times of less than 120 seconds.

Out of 82 identified uses for an EWS, respondents reported the estimated savings as follows:

- 14 (17 percent) reported savings ranging between $5,000 and $30 million. The mean and median of the 14 estimated savings responses are $4.6 million and $1 million, respectively.
- 32 (39 percent) gave no dollar amount as savings.
- 36 (44 percent) responded that the savings were "unknown."

Less than one-fifth of the EWS users indicated specific dollar amounts in response to the estimated savings question. Although the balance (83 percent) of the responses did not include specific dollar amounts, we cannot assume that these responses are equivalent to zero. As noted in the previous chapter, the lack of specific responses is probably related to the difficulty in estimating such savings under the considerable uncertainty associated with earthquake damage. Thus, while we cannot safely assume that the average reported savings are representative of all EWS users, we also cannot estimate savings from the nonspecific or "unknown" responses.

Of the 82 identified uses, respondents reported the false alarm costs as follows:

- 18 (22 percent) reported costs between zero dollars and $1 million. The mean and median of the 18 false alarm responses were $67,000 and $1,000, respectively.
- 47 (57 percent) gave no dollar amount as costs.
- 17 (21 percent) responded that the costs were "unknown."

Again, only about one-fifth of the respondents gave specific dollar amounts to the false alarm costs question. In this case, many more of the respondents gave no dollar amount than with the estimated savings question while fewer responded that the costs were "unknown." Once again, while we cannot safely assume that the reported false alarm costs are representative of all EWS users, we also cannot infer these costs from the nonspecific responses. We note that nearly half of the responses indicate false alarm costs of zero dollars.

Because of the large variances in the estimated savings and false alarm costs given in the survey, we believe that these cannot be used credibly in a rigorous cost-benefit calculation. Thus, they will not be used for an economic evaluation of the EWS in Chapter Six. For purposes of reporting, however, we have included greater detail on these amounts and other survey results in Appendices E and F.

## Conclusions

The survey results indicate that 44 (36 percent) of the 121 returned surveys identified at least one use for an earthquake warning between 1 and 120 seconds prior to strong shaking. A total of 82 uses were identified. This response, in itself, indicates that there is an interest in and desire for some type of earthquake warning system.

Of those respondents indicating a use for an EWS, they generally:

- Desire long warning times (greater than 30 seconds).

- View the EWS as useful for mitigating damage in the categories of production (39 percent), personnel (23 percent), computers (20 percent), and facilities (18 percent).

Based on these results, we conclude that there is interest by large organizations in an earthquake warning system that provides between 1 and 120 seconds of warning. The economic merits of an earthquake warning system for these potential users and society as a whole, however, are less obvious.

## Survey of Small- to Medium-Size Manufacturers

To ascertain whether small- to medium-size organizations (from a few to a few hundred employees) might be more able to use an earthquake warning for their operations, as well as personnel safety, a second survey, limited to small- and medium-size businesses, was undertaken. This survey was conducted in an area of recent earthquake activity where the earthquake experience may have revealed to such businesses uses for an earthquake warning system that may not be readily apparent.

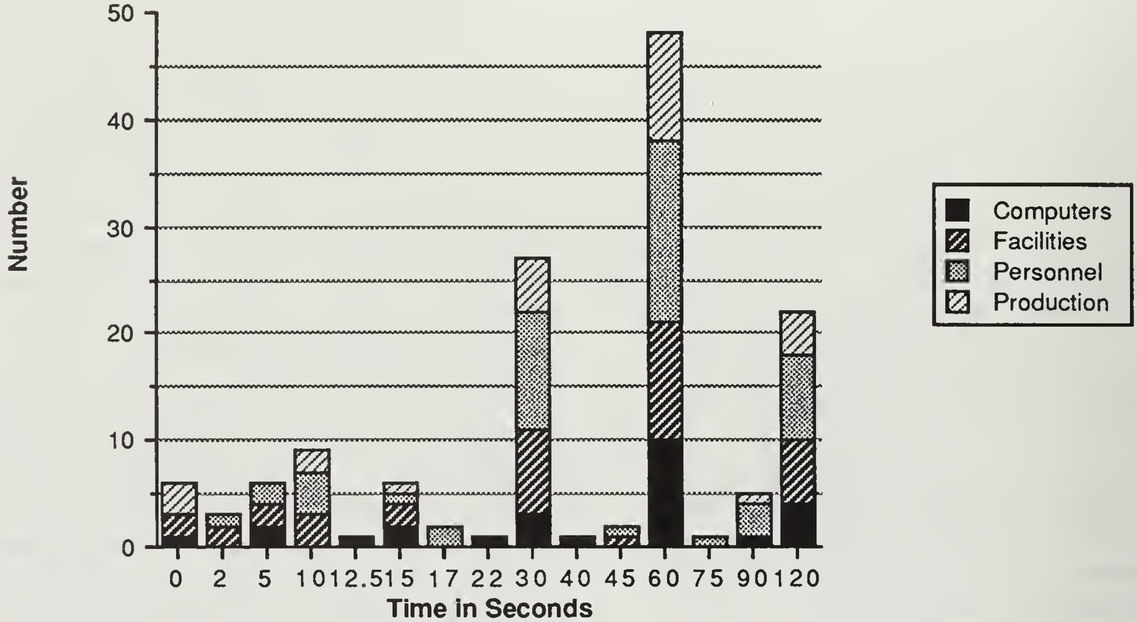
The task was contracted to VSP Associates Inc. of Sacramento, an earthquake preparedness and emergency response planning firm. A survey of 78 small- and medium-size businesses located within 10 miles of Whittier, California, was conducted. The purpose of the survey was to see if businesses of 10 to 250 employees had interest in and use of a warning a few seconds to a few tens of seconds prior to strong ground shaking.

## Uses

Of the 78 small- and medium-size businesses surveyed, 22 (28 percent) suffered damage, mostly nonstructural, in the Whittier Narrows earthquake. Nevertheless, more than 60 percent of the respondents had committed no resources to earthquake safety. While 58 percent felt that an EWS would be beneficial to their business, they would not want it to trigger an automated response, such as shutting off equipment. Respondents preferred those decisions to be left to human judgment.

As in the survey of large organizations, respondents generally

## Figure 3.3
## Types of Uses and Desired Warning Times
## Survey of Small- and Medium-Size Manufacturers near Whittier




| Times | Computers | Facilities | Personnel | Production | Totals | Percent |
|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 0 | 3 | 6 | 4 |
| 2 | 0 | 2 | 1 | 0 | 3 | 2 |
| 5 | 2 | 2 | 2 | 0 | 6 | 4 |
| 10 | 0 | 3 | 4 | 2 | 9 | 6 |
| 12.5 | 1 | 0 | 0 | 0 | 1 | 1 |
| 15 | 2 | 2 | 1 | 1 | 6 | 4 |
| 17 | 0 | 0 | 2 | 0 | 2 | 1 |
| 22 | 1 | 0 | 0 | 0 | 1 | 1 |
| 30 | 3 | 8 | 11 | 5 | 27 | 19 |
| 40 | 1 | 0 | 0 | 0 | 1 | 1 |
| 45 | 0 | 1 | 1 | 0 | 2 | 1 |
| 60 | 10 | 11 | 17 | 10 | 48 | 34 |
| 75 | 0 | 0 | 1 | 0 | 1 | 1 |
| 90 | 1 | 0 | 3 | 1 | 5 | 4 |
| 120 | 4 | 6 | 8 | 4 | 22 | 16 |
| Totals | 26 | 37 | 51 | 26 | 140 | 100 |
| Percentage | 19 | 26 | 36 | 19 | 100 | |

requested long warning times. The 78 respondents to the survey indicated 140 uses of an earthquake warning between 0 and 120 seconds. The mean and median warning times indicated were 52 and 60 seconds, respectively. In comparison, the mean and median warning times for large organizations were 72 and 60 seconds.

As shown in Figure 3.3, the profile of uses and times is similar to that shown for the large organizations (see Figure 3.2) in that responses are generally 30 seconds or greater and are gathered around the 30, 60, and 120 second intervals. In the small- and medium-size survey, 57 percent of these uses required more than 30 seconds of warning time to effect action, compared to 74 percent in the large organization survey. (Warning times that were *30 seconds and greater* were indicated by 76 percent of the small- and medium-size respondents and 84 percent of the large organizations.)

The predominant application cited by small- and medium-size firms was for personnel actions (36 percent). Another 26 percent indicated facilities uses while computers and production uses each accounted for 19 percent of the total uses. This pattern of uses contrasts with the uses given in the large survey where production uses were predominant (39 percent). This result seems to support the hypothesis that large firms may be more cognizant than small firms of the possible operations uses of an EWS. In addition, small firms see more facilities uses than the large organizations and fewer production uses. In short, small firms are more concerned with personnel, utilities, and mechanical systems uses of an EWS. Computer and production uses are less important, perhaps reflecting the less sophisticated systems employed at small manufacturing operations.

The respondents indicated that one or two false alarms in a five year period would be tolerable. However, if false alarms occurred more than about once a year, the system would cease to be worth the costs incurred.

## Conclusions

Small- and medium-size manufacturing firms desired less warning time, on average, than the large organizations. While 84 percent of the large firms gave warning times of 30 seconds or more, 76 percent of the small companies indicated these times. Thus, small manufacturers, like the large organizations, generally require relatively long warning times.

This survey indicated that there is support in the private sector for ongoing research into the reliability and applicability of an EWS. Nevertheless, respondents generally do not perceive the usefulness of an EWS as sufficient to warrant subscription. The system might have applications in the area of personnel safety, except that most respondents considered only building evacuation. A number of respondents felt that, should research continue and should a system be built with public funds, the signal should be made available to all members of the public.

## Expert Analysis of Worldwide Earthquake Experience Data

To assess the usefulness of an earthquake warning system to major industrial facilities, we contracted with EQE Inc., an earthquake engineering consulting firm, to review and evaluate their extensive earthquake experience data. The earthquake experience data consist of observations of earthquake damage, or lack of damage, to a variety of major facilities–structures and their internal components–throughout the world as a result of significant local earthquake activity. The earthquake experience data provides information on the seismic risk to certain types of facilities based on the performance of similar facilities in past earthquakes. Thus, based on actual damage, engineers can infer both the types of damage that can be expected at industrial facilities and the expected thresholds of ground motion that result in damage.

EQE evaluated how an earthquake warning might have been applied to mitigate damage and injury to the database facilities. The experience database is useful for the following reasons: (1) the experience data are reliably documented and (2) the results serve as a means of comparing the survey responses to earthquake experience as viewed by knowledgeable engineers.

Eight types of facilities were considered. In addition to providing the data summary, the EQE engineers reviewed the data and provided estimates of the amount of warning time, if any, that could have been used to mitigate damage to those facility types.

**Data Base**

The earthquake experience data have been collected over a period of years by sending experienced engineers to the epicentral area following a damaging earthquake. In the course of facility inspection, interviews were conducted with facility personnel. Also, written records, operating logs and photographic evidence of the damage were collected. (In many cases, these visits were conducted before repairs could be rendered.) When records of ground motion were not available for a particular facility, peak level and duration of ground motion were estimated. The manufacturer, type and age of equipment were noted.

The major types of facilities for which data were available are:

- Fossil-fueled and hydroelectric power plants,
- Electrical distribution substations,
- Oil processing and refining facilities,
- Water treatment and pumping stations,
- Natural gas processing and pumping stations,
- Manufacturing facilities, and
- Large commercial facilities, including hospitals.

Portions of the database consist of observations from 82 facilities damaged by 17 earthquakes. The magnitudes of the earthquakes represented in the data base range from 5.4 to 8.0, causing ground motions at the inspected facilities between 0.1g and 1.0g acceleration. Twelve of the 17 database earthquakes occurred in California (M5.5 to M7.0). Recorded strong motion at the facilities experiencing the earthquakes in California had peak accelerations between 0.1g and 1.0g and durations (for acceleration > 0.1g) from five seconds to more than 40 seconds.

### Typical Damage and Impact of Warning

The lead engineers responsible for collecting and processing the original experience data reviewed the data. Staff at EQE were asked to use their engineering expertise and judgment to estimate the value to the damaged facilities of a few seconds to two minutes of warning. The engineers were asked to evaluate the technical feasibility of devices that may be required to initiate a shutdown or start-up of equipment in response to a warning. In addition, the consequences of a false alarm were to be considered. For each type of facility, a summary of the data base for sites in each facility type (including earthquake, facility, description of site, major damage, estimated peak ground acceleration and distance from epicenter) was requested.

A summary of the results, given in Appendix H, includes data on facility type, the earthquakes and number of observations, and the consequences of false alarm. Facilities were grouped by the type of common equipment. The following is a discussion based on the results of the engineering analysis.

The use of an EWS to the electrical power industry appears to be very limited. For example, electric substations are arguably the most vulnerable component of the electrical power system (and correspondingly represent the largest number of power system observations in the data base). Most of the substation damage, however, has been to switchyard ceramics and transformers. In general, a warning would not have prevented such damage. In only one case (Sylmar Converter Station, 1971 San Fernando Earthquake) could small fires have been avoided by tripping the station. However, the consequences of a false alarm could be a serious perturbation to the power grid, possibly leading to a blackout over a large area for many hours. A warning could not provide sufficient time to spin-down generators or depressurize steam boilers after tripping fossil fuel or hydroelectric power plants. In many cases, vibration sensors on the generators automatically trip the plant; moreover, the experience data does not indicate damage to these components.

Pumping stations occasionally experience misalignment and binding of vertical pump shafts (to large underground wells). Where a minute or more of warning time could be given, it is believed that damage to this rotating equipment could be avoided.

The depressurizing of systems containing flammable substances was considered a possible EWS response to reduce the fire hazard at chemical and oil processing facilities. However, in many facilities there are dangers caused by the depressurizing itself, and the usefulness of warning would have to be examined on a case-by-case basis.

There was some evidence that the warning response of stopping or slowing large rotating machinery could mitigate damage to machinery in paper mills and to rolling equipment in steel factories. EQE noted that the 1987 New Zealand earthquake caused considerable damage to a paper mill there. The estimated warning time required for paper mills is approximately two minutes. The consequence of a false alarm would be the disruption of production and the time needed to restart the machinery.

According to the analysis of the database, hospitals and computer operations have never had a failure of backup power and/or an uninterruptible power supply during an earthquake, if their facilities or systems are properly engineered. In instances where systems such as uninterruptible power supply batteries were not anchored, systems did fail. Thus, there appears to be little advantage to "power-up" emergency systems on warning. The data on hospitals were primarily limited to structures, piping and duct systems, heating, ventilation and air conditioning. Warning did not appear to have an application to those systems. There may be medical equipment, emergency systems and/or life-support systems at risk but not included in the data base that could make use of an earthquake warning. One advantage to computer facilities that do not have or could not practically install uninterruptible power would be the automatic saving of computer work in progress, before power is lost to the computer. However, because most documented damage to computer systems in the past has been structural, e.g., failed "computer floors" and damage from the movement of unanchored devices, protection against loss of utility power may not effect substantial savings.

### Earthquake Experience Data Conclusions

The fundamental conclusion from the seismic experience data is that, with very few exceptions, earthquake warning does not appear to be of significant value in the mitigation of damage to engineered structures or their internal components.

In general, the only potential applications that EQE engineers could foresee was in an area not included in their studies: personnel safety. It was felt that personnel safety could be improved by the use of EWS at every type of facility except electrical substations and water pumping plants, which are not typically manned. Personnel safety uses were considered especially important at factories where employees could benefit from some time to clear away from dangerous substances that could otherwise spill or overturn on them.

### Summary and Conclusions

Respondents from both surveys indicated a number of uses for an EWS. Both of the groups surveyed indicated a desire for warning times of 30 seconds or greater. In fact, many indicated warning times of more than 60 seconds. The earthquake experience data corroborated the result that there appear to be few uses for short warning times (less than 30 seconds). Both large and small survey respondents indicated many personnel safety uses for an EWS. A number of respondents revealed an interest in post-shaking information. Many expressed concern over a system which generates false alarms. The data indicate that potential users appear to be reluctant to pay for an EWS.

The results of the data collection suggest that, while there is interest in an EWS, many uses require long warning times (60 to 120 seconds). In addition, some of the indicated uses are of dubious merit (i.e., personnel safety uses involving evacuation). A system which addresses the need for long warning times will be presented in the following chapter.

# CHAPTER FOUR–SYSTEM DESIGN

In this chapter, we consider constraints on the operation of an EWS that result from the physical characteristics of the earth, such as fault location and expected earthquake magnitude, the geographic location of potential users, and from the responses of potential users of an EWS.

### Seismological Constraints

Significant damage from moderate-sized earthquakes is generally limited to a few kilometers or few tens of kilometers from the fault rupture. Data from historic earthquakes in California (see Chapter Two) can provide a basis for the estimation of the damage distribution of significant damage from future earthquakes. Those data and the seismic intensity prediction model of J. Evernden of the U.S. Geological Survey were used to estimate the areas of significant damage–Modified Mercalli Intensity VIII or greater (see Appendix C for a description of the intensity scale)–for several different earthquake scenarios in southern California.

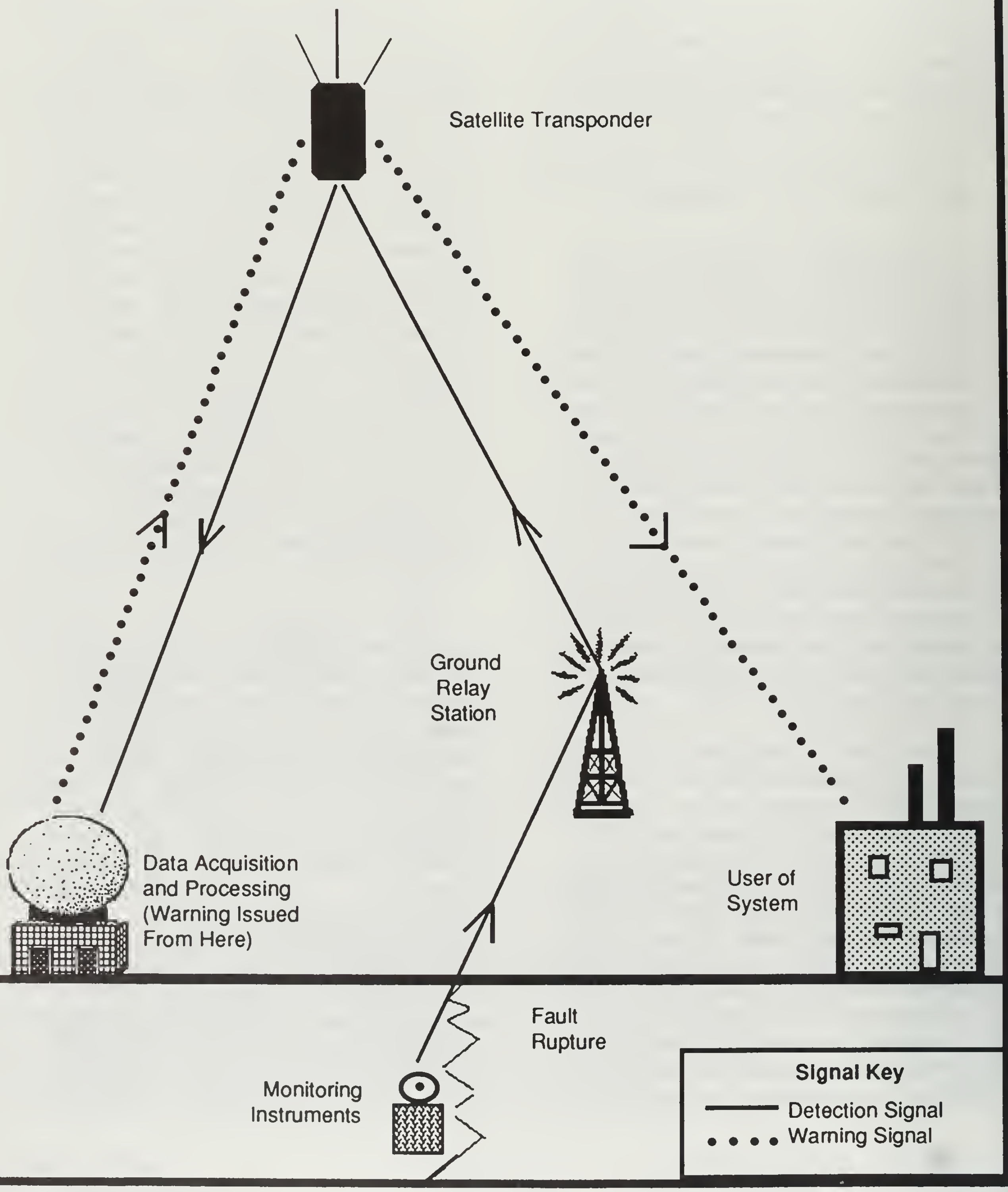
For the purposes of this discussion, "warning time" is the time between the issuance of the warning and the arrival of the shear wave (S-wave) which travels in the earth's crust with a velocity of about 3.5 km/second. Strong shaking will begin shortly after the arrival of the S-wave. The S-wave follows the arrival of the faster, but usually not damaging, primary wave (P-wave) which travels in the earth's crust with a velocity of about 6 km/second. Thus, the P-wave could be, and, in a number of installations, is used as a "built-in" warning of stronger shaking to follow.

One possible warning system configuration is illustrated in Figure 4.1. Ground motion sensors would operate along the fault at approximately 10 km (6 mile) intervals (note that the purpose of this array of instruments is not to locate the earthquake, but to detect its occurrence and estimate its "size"). Data from the sensors are transmitted by satellite to a central data analysis center, where a decision to warn is made, based on the recorded levels of ground motion or other seismic parameters. (Detailed options for warning system components are discussed in Appendix I.) The warning is transmitted to users by satellite, commercial radio frequencies or microwave. The users' equipment may include audible or visual alarms or an automatic programmed response to the received alarm.

An example of the kind of warning times attainable with an EWS is shown in Figure 4.2. In southern California, the Newport-Inglewood fault constitutes a significant earthquake hazard to the Los Angeles Basin. A magnitude 7.0 earthquake on the Newport-Inglewood fault zone could rupture the fault for 50 km (31 miles) (as shown by the straight, heavy line in Figure 4.1). We assume that the earthquake initiates at a depth of 10 km below its epicenter at the Baldwin Hills and ruptures the fault to the southeast. Approximately 4.7 seconds after the P-wave first reaches the earth's surface, the seismic S-waves have triggered two earthquake warning monitors. Assume that the warning is issued

## Figure 4.1

**Schematic Drawing of An Earthquake Warning System**



## Figure 4.2 Postulated Magnitude 7.0 Earthquake on the Newport-Inglewood Fault

(and received by users) one second later. Given these assumptions of earthquake location and system overhead, the warning times can be calculated. These warning times are illustrated in Figure 4.2 as concentric circles about the epicenter. All points within the innermost circle (which has a radius of about 14 km) would receive the warning *after* the beginning of strong motion, due to the 5.7 seconds of overhead. Arcs corresponding to 5, 10 and 15 seconds of warning are also shown. The heavy oval line surrounds the area that could experience significant damage (intensity VIII or greater) as a result of shaking from this postulated earthquake. Thus, approximately 80 percent of the significantly damaged area could receive a warning of from one to 15 seconds before the arrival of strong shaking. On the other hand, only about 10-20 percent of the intensity VIII area would receive greater than 10 seconds of warning, and practically no damaged areas would receive 15 seconds or greater of warning.

The warning times shown in the figure are fairly liberal. Very little in the way of data analysis or transmission delays have been incorporated into these initial numbers. Some time–only about three seconds–could be gained if the restrictions on a warning decision were relaxed even further. For example, the system could warn on one trigger only, rather than confirming with a second seismograph that a real earthquake is underway. Another less constraining option would be to trigger on the P-wave at only one station, rather than waiting for the S-wave to arrive at the closest stations. However, false alarms will increase as restrictions are relaxed, and reliability of the system to provide accurate warnings would suffer.

## User Constraints Based on Survey

As discussed in the previous chapter, 74 percent of the survey respondents indicated that long warning times–31 to 120 seconds–would be necessary to effect mitigating action. Very few respondents identified uses for short warning times (30 seconds or less). Thus, few of the respondents would benefit from a system providing coverage of faults with expectable earthquakes of M7.0 (such as the Newport-Inglewood fault, discussed above) or less. This, in effect, would eliminate from consideration nearly all faults within the Los Angeles Basin proper.

On the other hand, the survey response data suggest that users could benefit from a warning system that concentrates on very large earthquakes (M7 or greater) along the San Andreas fault north of Los Angeles. Although a repeat of the great 1857 earthquake (M8.3) is not thought to have a high probability of occurring within the next 30 years, there is a high probability (60 percent) of a M7.5 or greater occurring within the next 30 years along the Mojave and/or Coachella segments of the San Andreas fault near Los Angeles (see Chapter Two). The configuration of a warning system designed to cover those fault segments, consisting of a linear array of monitors spaced ten kilometers apart, is illustrated in Figure 4.3.

The system outlined above could provide useable warnings for earthquakes illustrated in Figure 4.4a-c. In each case, we have assumed a particular earthquake epicenter and fault rupture. We also assume a particular warning system configuration,

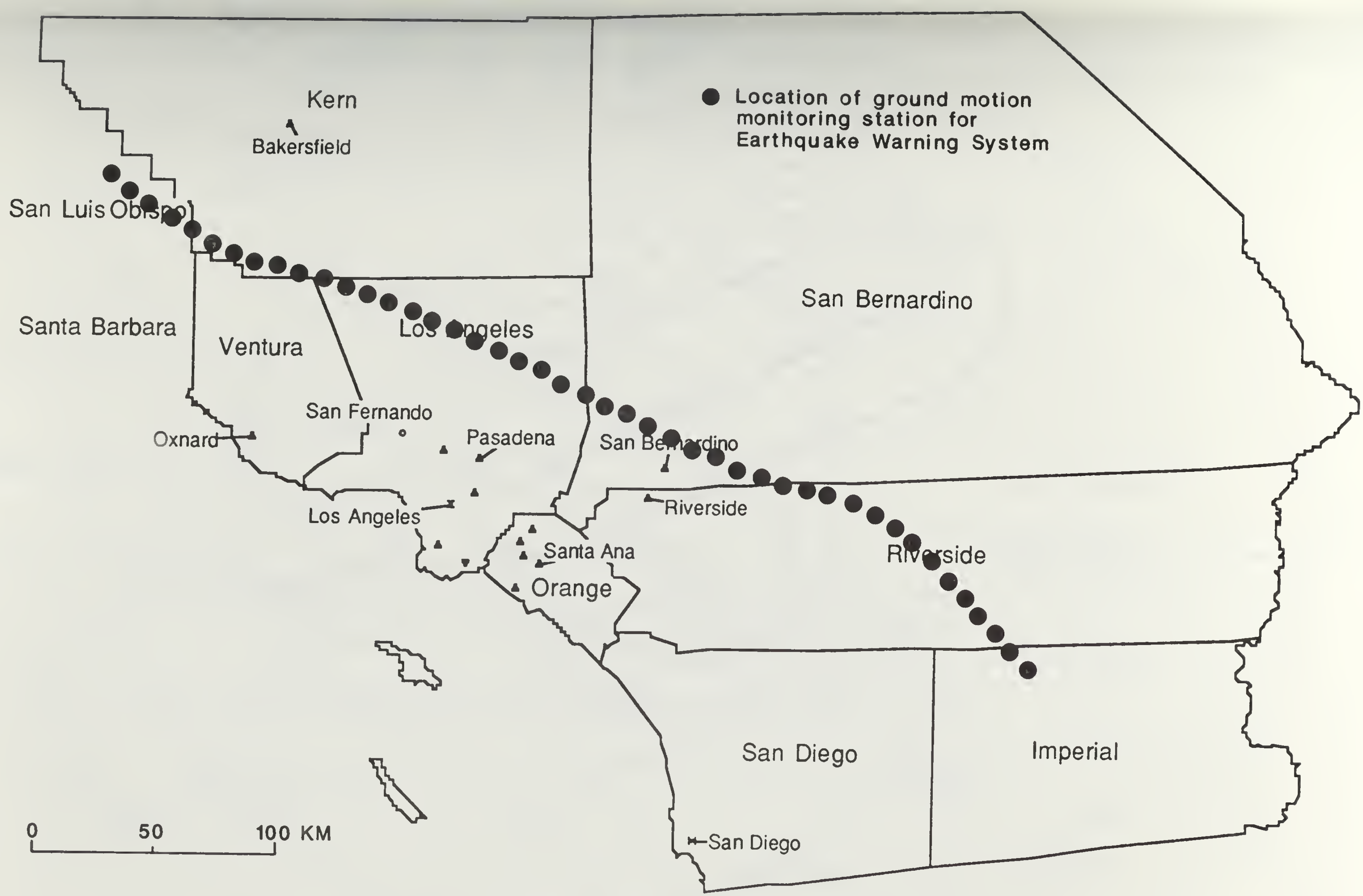



Figure 4.3 Schematic of sensor locations (10 km spacing) for an Earthquake Warning System to monitor the southernmost San Andreas Fault.

**Figure 4.4a Postulated Magnitude 7.3 Earthquake on the Mojave Segment of the San Andreas Fault Epicenter near Lebec**

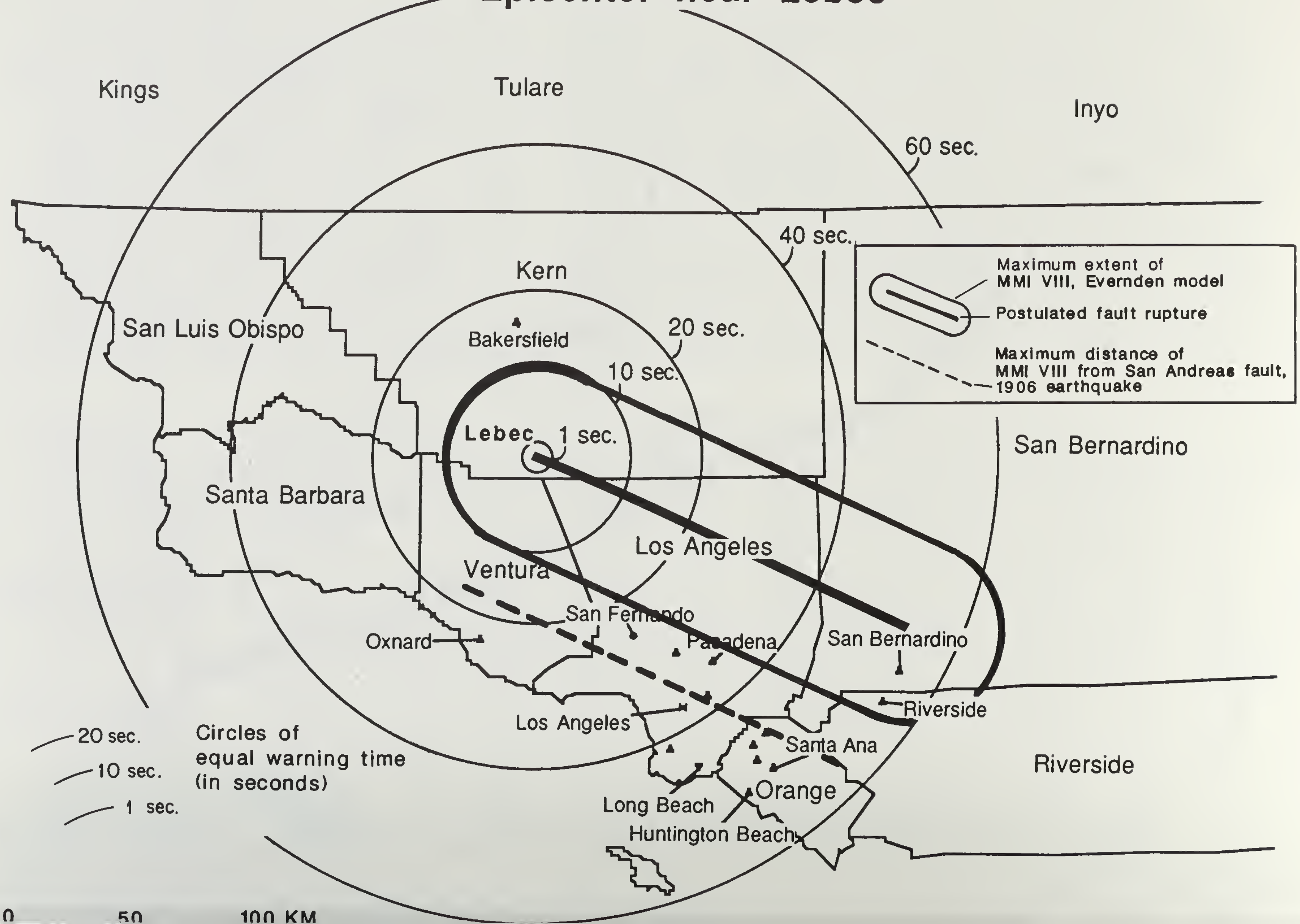


Figure 4.4b Postulated Magnitude 7.3 Earthquake on the Mojave Segment of the San Andreas Fault Epicenter near San Bernardino

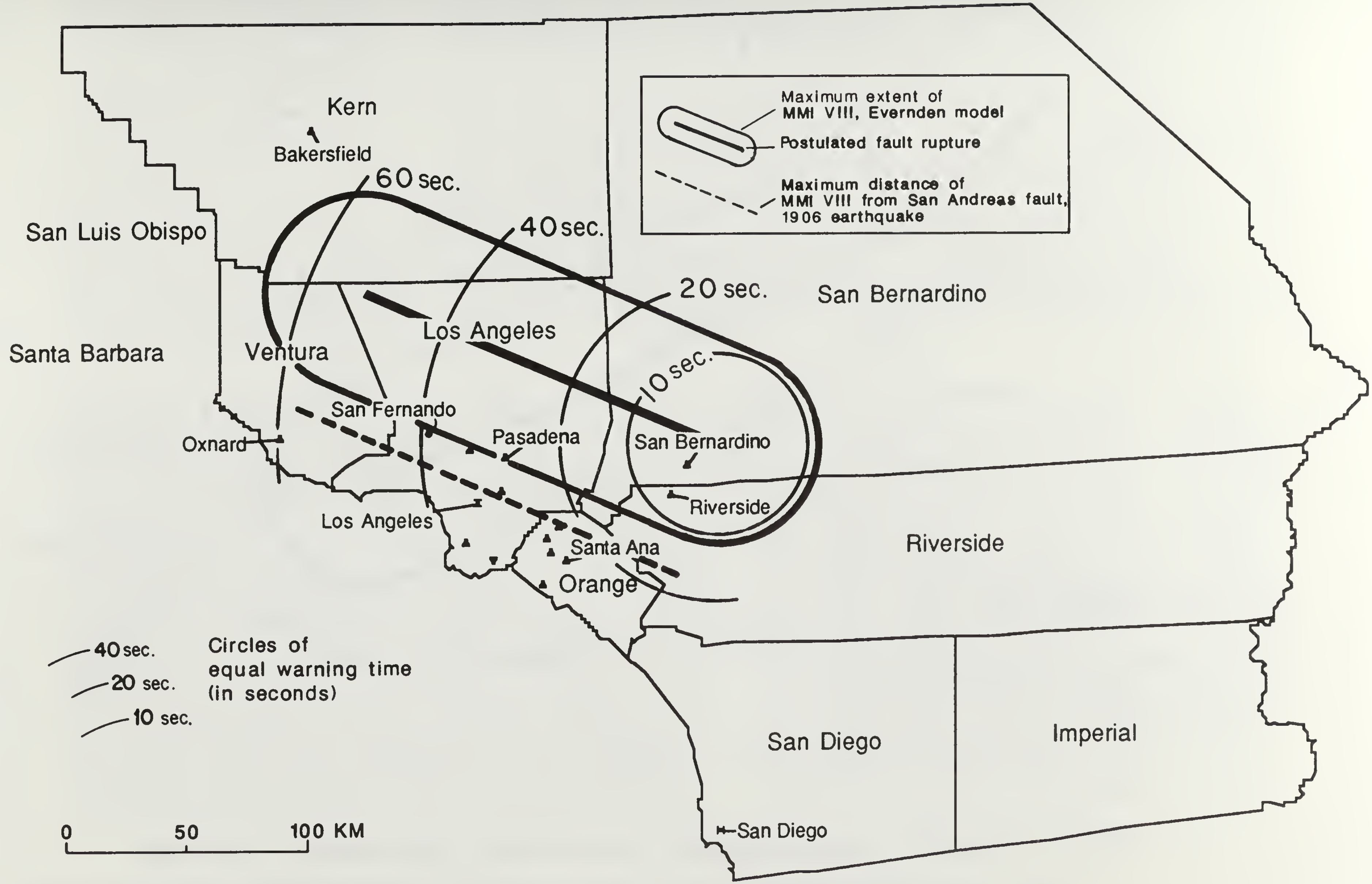
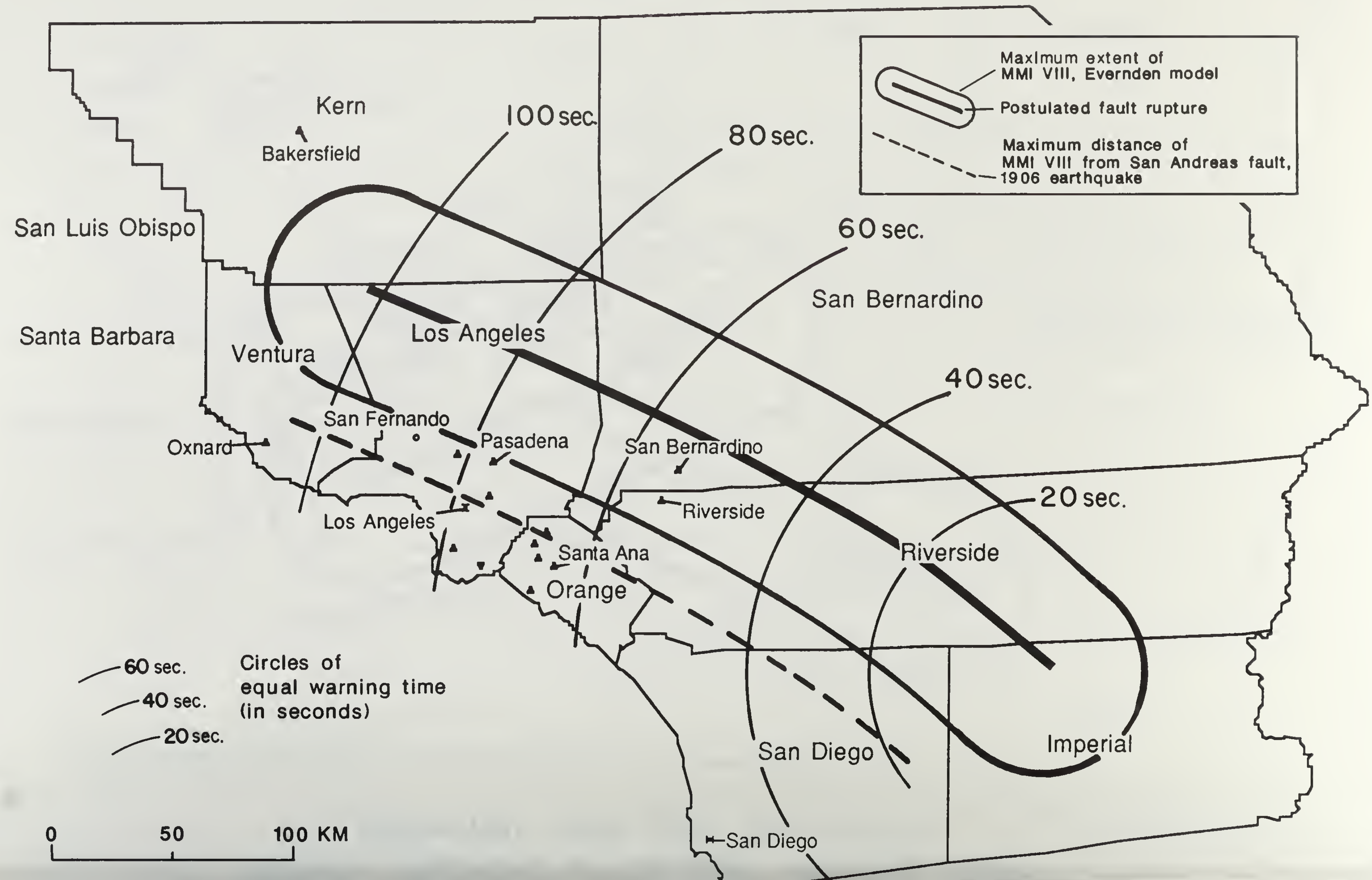


**Figure 4.4c Postulated Magnitude 7.8 Earthquake on the Mojave-Coachella Segments of the San Andreas Fault**



that has a system overhead of only three seconds.

Figure 4.4a postulates a M7.3 earthquake along the Mojave segment of the San Andreas fault, with an epicenter near Lebec, the fault rupturing toward the southeast. The heavy straight line represents the surface fault rupture. The heavy oval line represents the extent of Modified Mercalli Intensity VIII from the model of J. Evernden of the U.S. Geological Survey. The dashed line indicates the distance from the San Andreas fault at which intensity VIII was observed in the San Francisco Bay area following the M8.3 1906 earthquake. Thus, significant (short-period ground motion-induced) damage from the postulated event could extend into the northern San Fernando and San Gabriel valleys. Some damage (probably nonstructural) to long-period systems could occur as far away as coastal Orange County. The concentric circles, radiating from the earthquake epicenter, indicate the amount of warning time available at given distances from the epicenter. Thus, San Fernando and Pasadena would receive a maximum warning of approximately 25 and 35 seconds, respectively. San Bernardino would receive a maximum of 50 seconds of warning.

Two other possible earthquake rupture scenarios are illustrated in Figure 4.4b and 4.4c. Figure 4.4b assumes the same fault rupture as that in Figure 4.4a, a M7.3 earthquake rupturing the entire Mojave segment of the San Andreas fault, but with an epicenter near San Bernardino. In this case, San Bernardino receives virtually no warning. The San Gabriel and San Fernando valleys still receive a maximum of approximately 25 to 35 seconds of warning. The largest warning would be available to the relatively sparsely populated region of southern Kern County and northeastern Ventura County.

A number of seismologists believe there is evidence that the most likely place for a large earthquake to initiate is at the end of one of the fault's distinctive segments. If they are correct, the epicenter of the postulated Mojave earthquake would most likely be at one of the two sites shown here (Figure 4.4a,b). However, based on the current state of knowledge, the earthquake epicenter could actually be located anywhere along the fault rupture. Consequently, the actual warning times for a given location, such as San Bernardino, could be anywhere between the extremes illustrated in Figure 4.4a,b.

One final earthquake is postulated. As discussed in Chapter Two, the most likely fault segments for a great earthquake in southern California are the Mojave and Coachella segments of the San Andreas fault. We have discussed the Mojave earthquake vis-a-vis a warning system in the previous paragraphs. An earthquake on the Coachella segment alone, of M7.3 or less, would inflict relatively little (short-period, ground motion-related) damage in metropolitan Los Angeles. Should a Coachella earthquake grow through San Gorgonio Pass and include the Mojave segment, however, an earthquake of M7.8 could result. This event is illustrated in Figure 4.4c. Note that the area of significant damage is significantly larger, but it does not extend much further from the fault than the damage areas for the M7.3 earthquakes. Also, possible warning times for the Los Angeles area are quite large, ranging from a maximum of more than 50 seconds in Riverside and San

Bernardino to nearly 90 seconds in the northern San Fernando Valley. Although this postulated event offers the largest maximum warning times and therefore the most possible uses for a warning system, the likelihood of this event compared with that of the individual segments rupturing separately cannot be estimated at this time. Also, the probability that this earthquake would not grow into a M7.8, but be confined to the Coachella segment, is at least equal to probability of the larger event itself. Thus, there is a good likelihood that a warning system would issue a "false alarm" (in the sense that although a M7.3 earthquake did occur on the Coachella segment, it would cause very little damage in the Los Angeles area).

The modeling of Modified Mercalli Intensity is based primarily on damage to structures that respond to high frequency ground motion (i.e., to older construction and to one- and two-story buildings). Thus, the distributions in seismic intensities shown in Figures 4.4a-c are appropriately applied only to that type of structure. High frequency ground motion dies off with distance from the fault much more rapidly than does low frequency ground motion. The low frequency energy, which may have significant amplitude at greater distances from very large earthquakes, is not modeled here. Even though no one believes that conditions such as those that exist in Mexico City are widespread in the Los Angeles area, the effects of low frequency motion could be significant, though not necessarily catastrophic, at distances greater than those shown in the figure. Examples of low frequency structures include high-rise buildings, large liquid storage tanks and offshore oil platforms. There was, for example, nonstructural damage to high-rise buildings in downtown Los Angeles during the 1952 Kern County earthquake, centered near Tehachapi. Any of the events postulated in Figure 4.4 could inflict significant damage to poorly engineered or constructed low frequency structures in the Los Angeles Basin. The largest of the postulated events could inflict even greater damage.

Unfortunately, without specific data on low frequency energy generation by great California earthquakes on local site factors and on California building response, it is difficult to estimate the overall effects of low frequency ground motion. Nevertheless, few survey respondents with low frequency facilities or processes indicated that any of the offered warning times would be useful. Generally, respondents indicated that many minutes were required to effect mitigating action.

### Summary

The survey respondents' desire for long warning times (30 seconds or greater) severely limits the applicability of an earthquake warning system to those faults expected to generate earthquakes of M7.0 or greater. In southern California, this effectively limits an earthquake warning system to sections of the San Andreas fault between the Salton Sea and Parkfield. A system such as the one discussed would cost approximately $3.3 million in capital and installation costs (excluding personnel) and approximately $1.6 million in annual operation and maintenance costs (Appendix I). This estimate does not include the users' costs of purchasing and maintaining warning receivers and of integrating warning actuation into their systems. Depending on the epicentral location of a M7.3 or greater earthquake on the instrumented portions of the San Andreas fault, useful warning times could be provided to areas of significant damage in the north San Fernando and San Gabriel valleys and in the San Bernardino and Riverside areas. Longer warning times would be possible for facilities in southern Los Angeles and Orange counties, but these would probably be useful only to facilities sensitive to long-period ground motions.

Because the San Andreas fault in southern California is very quiet, a relatively simple warning decision process, with low system overhead time, could be implemented. Such a system would probably trigger on nearby large events such as the 1952 Tehachapi (M7.5), 1971 San Fernando (M6.4) and 1986 West Palm Springs (M5.6) earthquakes. Given the possibility of occasional system failures causing false alarms and of continued seismic activity on and along faults near the southern San Andreas, a more sophisticated system may be required to reduce the probability of false alarms (see Appendix I for discussion).

# Chapter Five–Real-Time Earthquake Information

The discussion in Chapter Four on Earthquake Warning System design and operational capabilities is based on the premise that the survey responses regarding warning times are, in fact, appropriate for potential uses of the system. Very short times were generally not thought to be significantly helpful. Several factors may have contributed to this somewhat surprising result.

- Respondents generally preferred to keep people within the decision chains, rather than trust an automatic response to a warning. This factor contributes significantly to the preferred long warning times.
- When considering personnel safety issues, respondents frequently requested sufficient time for building evacuation (often much more than two minutes).
- Survey participants were asked to provide the minimum useable warning times in a range of zero to 120 seconds. Respondents may have simply chosen the longest available time in order to maximize their options.

In light of these considerations, short warning times may be useful under the following conditions:

1. *Personnel Safety Actions.* A number of survey respondents indicated that personnel safety would be the primary reason for use of a warning system. Long times were requested, usually sufficient to enable building evacuation. However, an earthquake warning system could never guarantee enough warning time to allow complete evacuation. The hazards that could be encountered during an evacuation while experiencing strong shaking could outweigh the advantages of the evacuation. In fact, some studies have shown that more injuries occur to those who exit buildings than to those who remain inside (barring, of course, building collapse). Nevertheless, short warning times could give properly trained personnel the opportunity to quickly move away from a hazardous location (such as near a container of caustic liquid) and/or move to a safer location (such as under a desk). In general, the time required for an employee to effect such mitigating action could be very short. In addition, the costs of taking such action, even if the warning were a false alarm, would be small. This type of system could also be considered for residential use for the same reasons. Based on the fatalities during recent earthquakes, an EWS is unlikely to have significant lifesaving benefits. (For example, in the 1971 San Fernando earthquake, 49 of the 64 deaths resulted from structure collapse or falling debris. In the 1987 Whittier Narrows earthquake, one death occurred as a result of falling debris.)

2. *New Uses for an Earthquake Warning System May Develop.* A number of respondents indicated that automated response to an earthquake warning is undesirable, thus resulting in warning times that are not reliably attainable by an EWS. If an EWS were

to be developed and proven to be reliable and effective, potential users might then accept and utilize automatic switching and response capabilities.

3. *Public Alerting Capabilities.* A public alerting system operates in the Tokyo/Kanto area. Loudspeakers are placed in schools and scattered throughout the cities and countryside. Public announcements notify listeners after an earthquake has occurred. The systems in Nakano, Chiba and downtown Tokyo are automatically activated to broadcast tape-recorded messages over loudspeakers. A pre-recorded message, informing the public that an earthquake is occurring or is about to occur and giving brief instructions on what actions to take, could be broadcast over an extensive public address system, after activation by an warning system. In addition, the Emergency Broadcast System (EBS), or other radio-frequency broadcasting systems, could be supplied with pre-recorded messages to be issued upon receipt of a warning signal.

## Short Warning Time System Options

If the potential uses of short warning times identified above support building an earthquake warning system, there are several options for providing this information. The options include a regional EWS and a local P-wave trigger system. One further option, drawing on the same technology but providing "post-shaking" information to emergency response agencies is discussed.

### Regional Earthquake Warning System

A regional earthquake warning system would consist of a number of ground motion sensors distributed throughout the metropolitan area in a grid-like pattern. (Before the October 1, 1987 Whittier Narrows earthquake, only the known hazardous faults in the Los Angeles area might have been considered for monitoring. However, if the entire seismic hazard is to be addressed, it is now clear that a distributed system is required.) One possible station distribution for the Los Angeles area is illustrated in Figure 5.1. A coverage of the entire greater Los Angeles metropolitan area with a sensor spacing of about 10 km would require approximately 110 stations. Closer spacing would not improve system timing; wider spacing would increase system overhead. For example, 10 km spacing would have a basic overhead time (the time required after the origin time for the S-wave to trigger two or more sensors, assuming a source depth of 12 km) of about five seconds. Spacing of 20 km and 30 km would have basic overhead times of seven and ten seconds, respectively. If the extra two to five seconds is insignificant compared with data processing time or with the distance from the fault (e.g., the San Andreas fault) to population centers, then the wider spacing could be sufficient. Alternatively, the time required for the P-wave to trigger two or more stations 10 km apart is about two seconds. Attempts to issue a warning based on P-wave triggers, however, could result in an increased false alarm rate from non-damaging earthquakes.

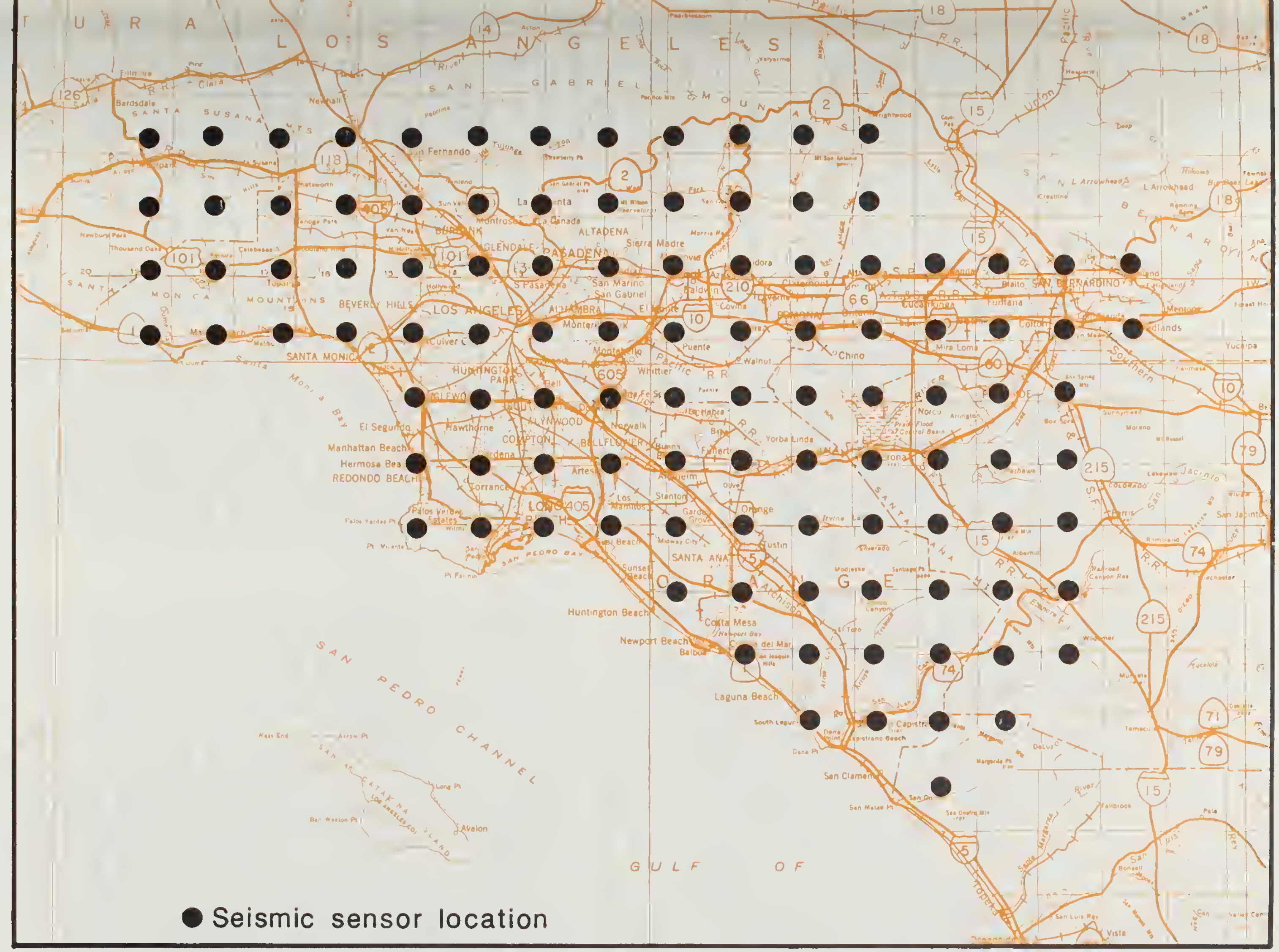



Figure 5.1 Possible monitoring station distribution for a Los Angeles regional warning system.

Shown in Figure 5.2a is the seismic intensity distribution of the M5.9 Whittier Narrows earthquake. The area that experienced intensity VIII is very small. The area of intensity VII is larger, but damage at this level is light, except for poorly constructed and unreinforced masonry buildings. If a warning is issued one second after two stations detect "significant" P-wave energy, warning times available to users for shaking from the Whittier Narrows earthquake would be as shown (dashed circles) in Figure 5.2a. Note that the maximum warning to a user who experienced intensity VII would be only five seconds. The particular decision algorithm used here would be prone to false alarms (e.g., a warning could be issued for shaking that does not cause damage). More reliable trigger algorithms would require either more sophisticated data analysis and/or waiting until the earthquake was better developed. Either would substantially increase the overhead time. Thus, an earthquake warning system may not provide *useful* warning at all for earthquakes of magnitude near M6.

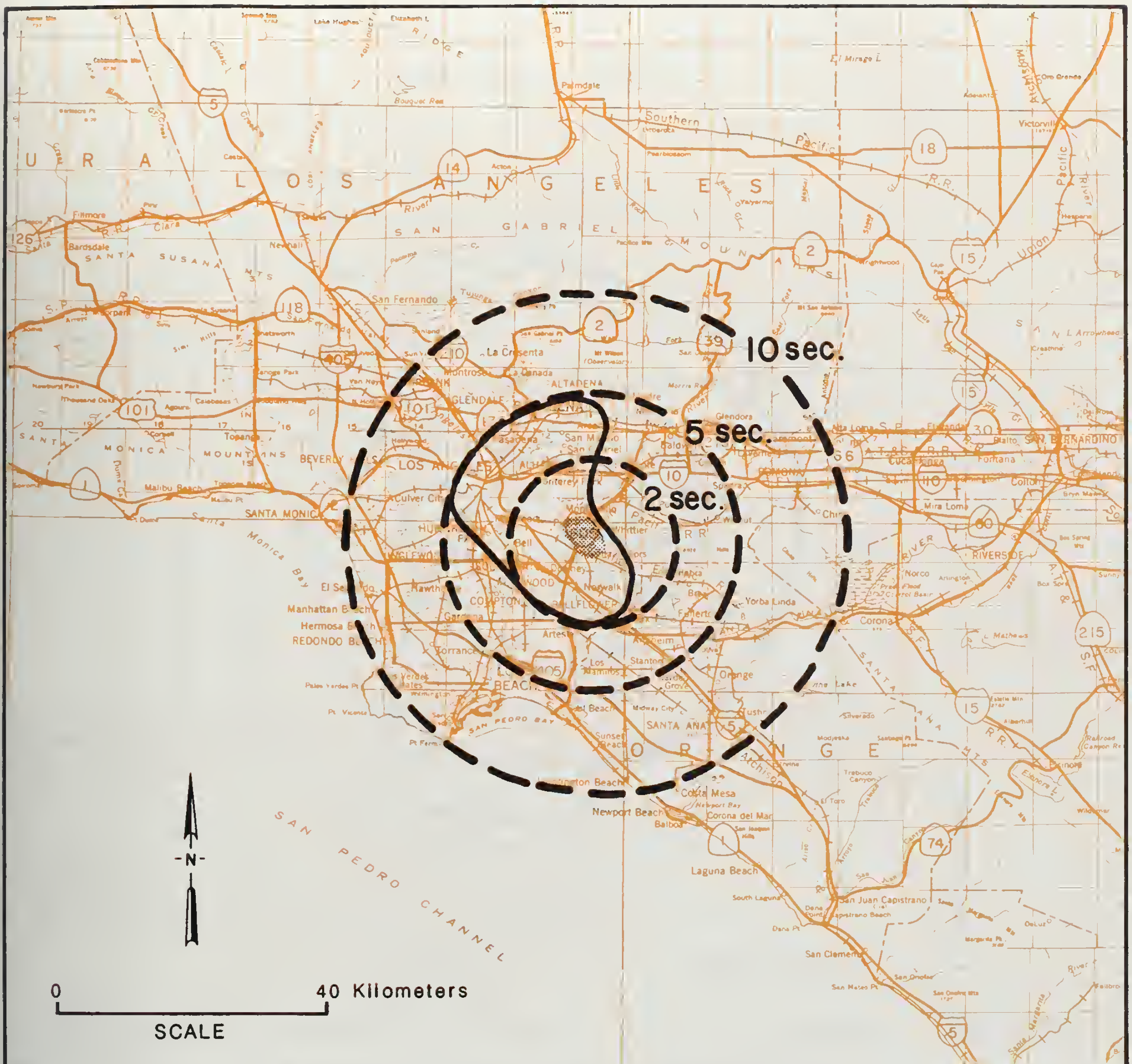
In order to explore a little further the possible usefulness of a distributed, regional warning system, consider the scenario shown in Figure 5.2b. The epicenter and seismic intensity contours are from the February 1971 San Fernando earthquake (M6.5). As shown in Figure 5.2b, the more heavily damaged portion of the San Fernando Valley could have received between about two and five seconds of warning (given a minimum system overhead) before the onset of strong shaking. This may represent the lower limit of usefulness for a distributed system. A potential user should keep in mind that, historically, earthquakes of about this magnitude have occurred in the Los Angeles area approximately once every decade. (For purposes of comparison, a M6 earthquake occurs somewhere in California about once each year.)

A straightforward extension of this regional system could be a subregional, distributed processing system. Some number of data processors could control the issuance of an earthquake warning over a restricted portion of the whole region. These processors could review all of the EWS seismic data or only the data from those stations closest to the subregion. This could provide a more finely tuned, geographically more accurate, warning. The disadvantages of the system would be increased cost, as each subregion would have its own processor, and a decrease in possible warning time if each processor uses only the data in its vicinity.

**Local, P-Wave Warning System**

As mentioned above, anyone near a damaging earthquake may already know that an earthquake was in progress before the onset of damaging ground motion (i.e., before the arrival of the S-wave). In Figure 5.3, we compare the expected warning times of a distributed system with the time that would be available if the warning were issued locally at the time of the arrival of the P-wave. Note that, out to about 10 km (6 miles), the local trigger actually does better than the distributed warning system. This is because of warning system overhead (requiring two stations to "trigger" on a P-wave and allowing one second for a decision). As warning algorithms become more complicated and warning system overhead increases, the distance at which a warning system's performance equals the performance of a local P-wave system increases. Thus, for 5.7 seconds of overhead (dashed line), the

Figure 5.2a




1987 Whittier Narrow Earthquake, M5.9

MODIFIED MERCALLI INTENSITY

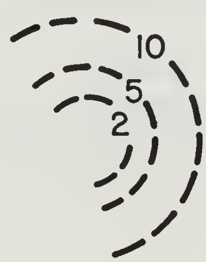
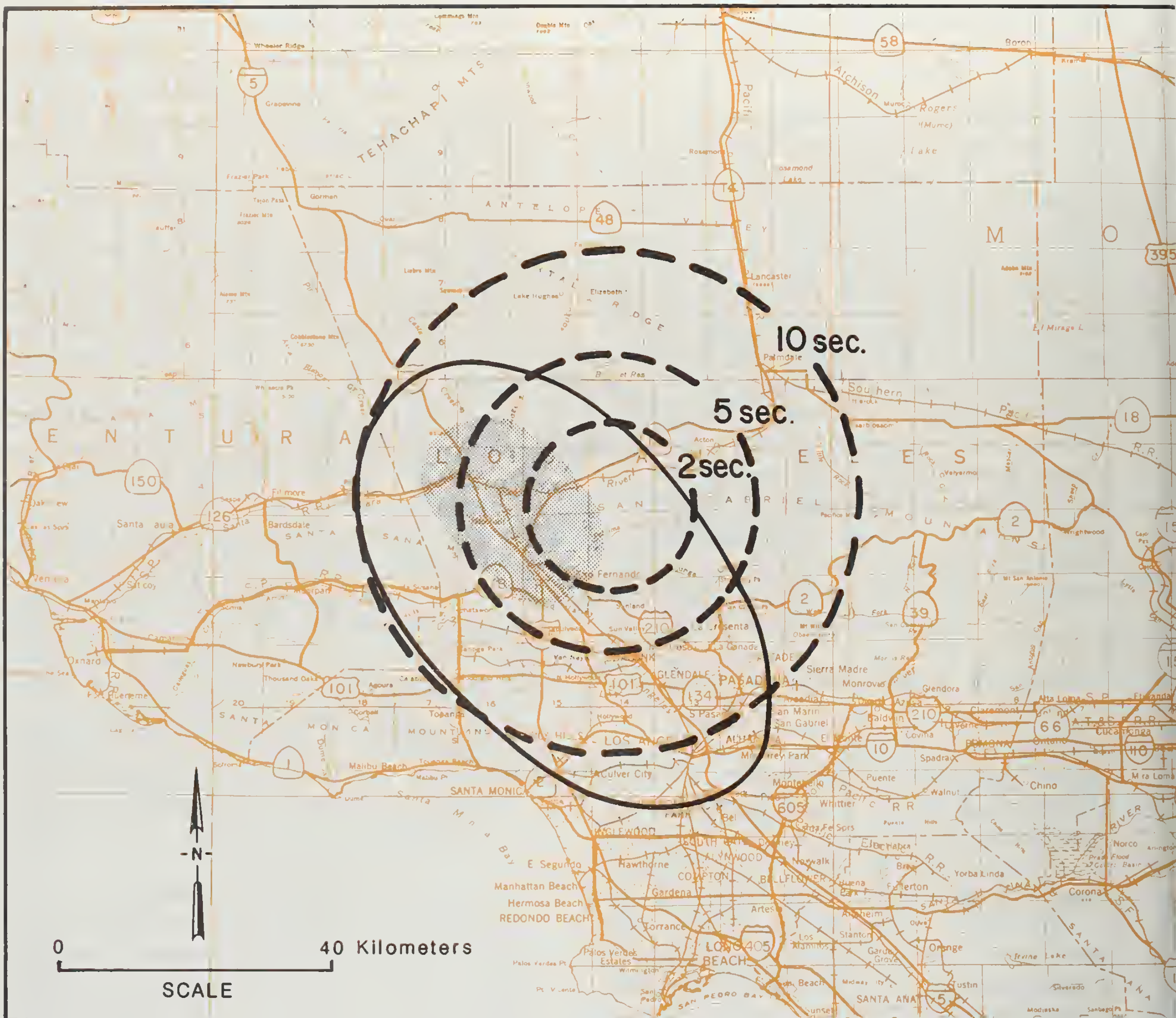




Figure 5.2a Modified Mercalli Intensity distribution (VII and VIII) for the 1987 Whittier Narrow earthquake, M5.9, and potential warning times.

Figure 5.2b




1971 San Fernando Earthquake, M6.5

MODIFIED MERCALLI INTENSITY

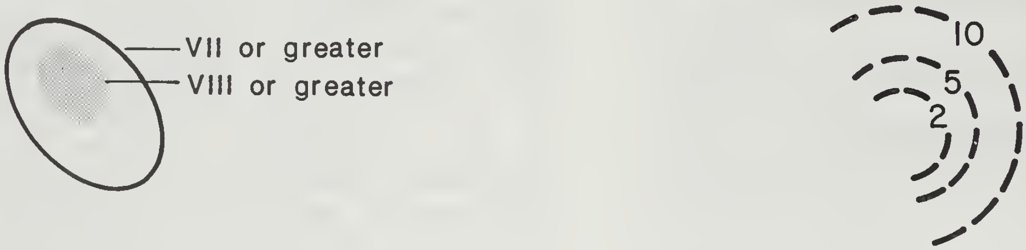



Figure 5.2b Modified Mercalli Intensity distribution (VII and VIII) for the 1971 San Fernando earthquake, M6.5, and potential warning times.

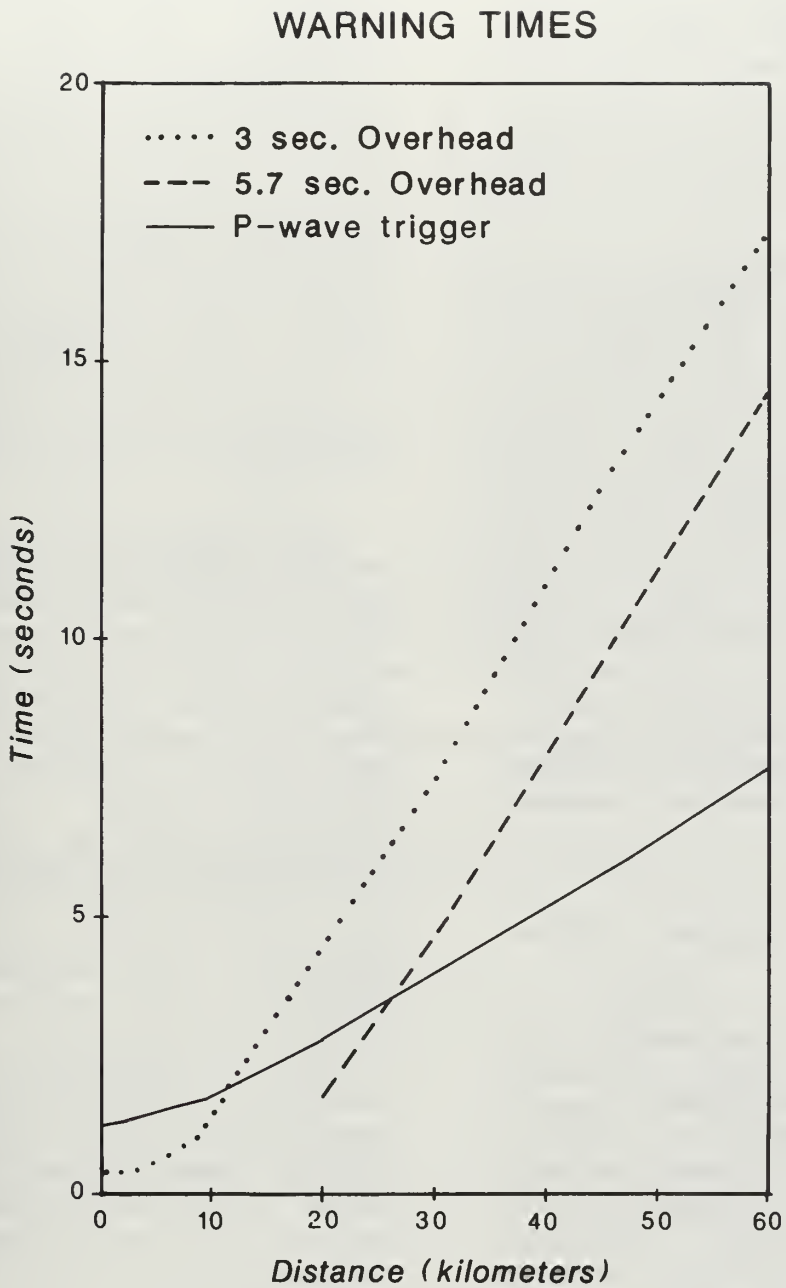



Figure 5.3 Comparison of possible warning times for two different system overhead times and for a local ground motion (P-wave) trigger.

crossover is at 27 km. That is, if a potential user is less than 27 km from an earthquake source, the P-wave will arrive at his location before an earthquake warning triggered by two S-wave sensors. The local trigger may be a preferred alternative if only very short warning times are required.

The local trigger is more prone to false alarms than a regional warning system. A relatively small event could trigger the warning, even though no damage occurred. If the level of ground motion required to issue a local warning is increased, the overhead time of the local trigger system is also increased. Thus, this type of system may not be useful for uses/processes with high false alarm costs. Nevertheless, it may be the most economical system for short-warning-time personnel and personal uses. A number of this kind of system, of varying degrees of sophistication and reliability, have recently become available commercially.

### Real-Time Earthquake Information System

A number of respondents to the large corporation survey, particularly those involved in emergency response, indicated that, while they had no particular use for a warning as such, they could use more rapid information on the earthquake's magnitude, location and resulting damage distribution. The latter is problematic because it is not yet possible to accurately predict the distribution of damage based solely on estimates of location and magnitude. On the other hand, the epicenter and magnitude can be accurately and rapidly estimated. Also, the regional warning system could allow rapid determination of the strength of shaking, from which it would be easier to estimate the damage distribution. The most economical implementation of this service might be an augmentation of the existing California seismic networks, such as those operated by the U.S. Geological Survey, California Institute of Technology, California Department of Water Resources, the University of California and the University of Southern California. Some centralized management structure might be desired to integrate these networks and transform them into true round-the-clock operations.

The data from the existing seismic stations would provide the basic information for an initial estimate of the earthquake epicenter. But existing stations do not provide good magnitude data for large earthquakes. Also, their communication lines are generally not hardened against earthquake effects. It would be necessary, then, to augment the existing networks with some number of seismic stations capable of providing magnitude data for the largest earthquakes. If only magnitude data is required, only a few stations (say, nine throughout California) would be necessary. If these stations are also to provide data for earthquake location (contingency for failure of the high-gain networks' communications lines), some greater number of stations would be necessary, the number depending on the earthquake location accuracy required.

In addition to new seismic monitoring stations, the network operator(s) may require additional computing capacity to assure that the data are analyzed as accurately as possible in real time. Also, some form of communication system (e.g., packet adio, see Appendix I) between the etwork computer and the emergency esponse agencies would have to be nplemented. Although the system vould automatically transmit the nformation to the user agencies, the etwork operator(s) would have to erify the automatic location and nagnitude in a timely manner so the ne occasional system error or failure ould be caught and corrected before ignificant emergency response esources are activated.

This augmentation would require n additional commitment on the part of ne network operators. Installation, peration and maintenance of this type f system may not fall under their urrent research or public information nandates.

**System Cost Estimates**

Approximate estimates of the cost of the systems discussed above can be generated given certain assumptions on sensor, data transmission and data analysis methods chosen from those discussed in Appendix I. Cost estimates are based on a relatively simple system that transmits pre-processed data from an array of strong ground motion sensors. Actual costs would depend on the actual options chosen and other possible uses of the data (such as seismological research) that are not built into these estimates. (Costs shown for the Los Angeles system include San Andreas fault-based stations as well as the regional L.A. stations.) Cost estimates are shown in Table 5.1.

**Table 5.1**

**Costs of Various Real-Time Earthquake Information Systems**

| System | Capital Costs (millions) | Annual Costs (millions) | User Costs For Receiver |
|---|---|---|---|
| Regional Los Angeles Basin | $4.4 | $2.2 | $40-$300 |
| Regional Los Angeles Basin and San Andreas | 5.8 | 2.4 | 40-300 |
| Local P-Wave trigger | – | – | 1,000-10,000 |
| Real-time Earthquake Information (Southern California) | 1.0 | 0.3 | 1000 |

User receiver costs indicate a range of costs to each user for the purchase of a receiver for the warning signal. They do not include the costs of incorporating that signal into the users' operations.

## Analysis and Conclusions

There may be potential uses for short warning times not identified by the respondents to our survey of potential users. These uses include, or are conditional on (1) personnel safety, (2) developing uses, and (3) public alerting capabilities. The development of an EWS based on (2) depends on the potential market that may develop over time and on the breadth of potential existing and future uses of an EWS. Unfortunately, the data do not indicate how extensive these uses may be. The development of an EWS based on (1) and (3) can be considered as a public health and safety issue. The benefits of providing earthquake emergency notification and alerting information to the public cannot be readily measured.

# Chapter Six—Economic Evaluation

The legislation initiating this study (Chapter 1492, Statutes of 1986) specifies that an evaluation of the economic feasibility of implementing the earthquake warning system include an "assessment of the value of warning to various elements of society." The assessment is to include an "estimate of the value of the warning as a function of warning time and its reliability." The purpose of this chapter of the report is to outline the economic parameters and constraints of an EWS for selected organizations.

This chapter will first discuss cost-benefit analysis generally and outline the various theoretical costs and benefits that could occur with an EWS. Next, the use of survey data in a formal cost-benefit analysis is discussed. To address the question of EWS feasibility under various conditions, decision rules will be developed which take into consideration different combinations of estimated savings/avoided losses, false alarm costs, and system attributes.

## Cost-Benefit Analysis

Generally, cost-benefit analysis attempts to answer whether a number of investment projects should be undertaken and, if investable funds are limited, which projects should be selected. To do this, cost-benefit analysis measures the weighted costs and benefits of a project. The stream of costs and benefits associated with a project over time is usually discounted to reflect the reduced value of money over time and to isolate the effects of inflation on the analysis.

A cost-beneficial project (benefits exceed costs) differs from one that is cost-effective in that cost-benefit analysis is concerned with the benefit or loss to society as a whole. A project that is cost-effective for an organization (that is, receipts exceed costs) may not be cost-beneficial to society, particularly if the indirect costs of the project are borne by other parties.

Cost-benefit analysis is subject to a number of limitations, including:

- The costs and benefits may not be readily measurable, thus the benefit or loss of a project may be understated.
- Cost-benefit analysis is sensitive to the rate of discount selected for the analysis.
- A project which results in overall net benefits may also make some parties better off while others are made worse off. Thus, cost-benefit analysis may not address the distributional effects that a project may have.
- Finally, the net benefit of a project may not be the most important decision criterion. Some projects that are cost-beneficial might not be funded, while others may be funded based on other decision criteria.

In this chapter, a modified form of cost-benefit analysis will be used to assess the savings and false alarm costs of an EWS. In addition, the analysis will indicate how effectively an EWS must perform for its users in order to be cost-beneficial.

## Theoretical Costs and Benefits of an EWS

The construction and use of an earthquake warning would involve a variety of both costs and benefits for potential users. The costs include the system costs plus warning-related costs; the benefits are the estimated savings and avoided losses that result from responding to an earthquake warning. In a cost-benefit analysis, these costs and benefits must be weighted by the probability of the occurrence of damaging earthquakes and the reliability of earthquake warnings. The following discussion outlines several of the theoretical costs and benefits that may result from the implementation of an EWS.

### Costs

The total costs of an earthquake warning system include the costs of the system, the costs related to responding to a warning, expectational costs, and potential liability costs. The system costs include the one-time capital costs to design, purchase, and install warning equipment, and the associated annual operations and maintenance costs. Warning-related costs may be subdivided into costs associated with the following warning possibilities (see Table 6.1 below):

- *True positive alarm* (damaging earthquake occurs and warning is issued) could result in a loss of productive capacity (to the facility and society) and/or potential damage and injuries in response to the warning. Ideally, these costs are offset by the potentially greater costs associated with an earthquake-induced loss of productive capacity or damages and injuries that would be incurred if there were no warning.
- *False negative alarm* (damaging earthquake occurs but no warning is issued). Although there is no warning response, there may be a cost associated with reliance on a warning system. If a warning system were not made available, users may have taken other measures which could have mitigated the resultant earthquake damage.
- *False positive alarm* (no earthquake occurs but a warning is issued) could result in the unnecessary loss of productive capacity (to the facility and society) and potential damages and injuries. In the case of a false positive alarm, there are no offsetting avoided losses to compensate the user for the down time resulting from a false positive warning. A variation of the false positive alarm is when a *non-damaging* earthquake occurs and a warning is issued.
- *True negative alarm* (no earthquake occurs and no warning is issued) will not result in costs since there is no response and (obviously) there are no consequences associated with the absence of an earthquake.

Expectational costs are those costs that could occur if, as a result of the installation of an EWS, there are changes in certain economic values. For example, property insurance rates could increase, land values could fall, or businesses could relocate from areas that are alerted or that are to be alerted by an EWS simply because individuals and organizations expect these changes to occur. These expectational changes may be the result of better information or an increased sensitivity to risk. Although the risk may not have changed as a result of the EWS, the existence of an EWS may increase (or decrease) fears of economic losses, thus resulting in a change in economic values. In either case, there will be winners and losers and these costs and benefits will "wash out" over society as a whole although they may be incurred by potential users of an EWS. For example, current property owners will lose if property values drop. Property purchasers, however, will benefit from a lower price. These costs (or benefits) cannot be estimated before an EWS is implemented, but they may be significant.

Potential liability costs include the losses that may be sustained if a warning (or lack thereof) results in judgments against an organization or developer/operator of an EWS. These costs are indeterminate but could be major. We will address the issue of liability separately in Chapter Eight.

**Table 6.1**

**Earthquakes and Warnings: Possible Configurations of Alarms**

| | **Warning** | **No Warning** |
|---|---|---|
| **Earthquake** | *True Positive* | *False Negative* |
| **No Earthquake** (or nondamaging earthquake) | *False Positive* | *True Negative* |

### Benefits

The benefits include the estimated savings or avoided losses that result from responding to a true positive warning. Research opportunities and increased earthquake awareness/preparedness may also be considered real benefits of an EWS. The savings/avoided losses may be measured in terms of potential reductions in damage to operations and equipment/facilities, injuries and loss of life.

The research benefits are those gains resulting from additional instrumentation and the consequent increase in knowledge about earthquakes and damage to structures and contents. It is not clear how to quantify the value of this potential increase in knowledge.

Finally, a warning system might confer general benefits on society in terms of increased earthquake awareness and preparedness and, indirectly, in improved emergency response capability. These awareness and preparedness benefits, however, may be achievable with alternative approaches that focus on increased public information and emergency response training.

## Cost-Benefit Analysis and the Survey Results

As we indicated in Chapter Three, the respondents indicating a use for an EWS were frequently not specific in their estimation of savings or false alarm costs, or in the amounts they were willing to pay for an EWS. In fact, about 80 percent of the respondents either gave no response or indicated that these amounts were "unknown." Clearly, these estimates are difficult to calculate given the considerable uncertainty associated with earthquakes and earthquake damage.

The specific responses to the savings and costs questions have large variances. The nonspecific responses (no response or "unknown") cannot be either assigned values or equated to zero. Certainly, if respondents that are familiar with their facilities are unable to provide savings and costs estimates of an earthquake warning at their site, we cannot estimate these values *a priori*.

Given the uncertainty resulting from the dearth of specified data points and the variance in the specific responses, *we conclude that the estimated savings and false alarm costs data from the survey cannot be credibly used in a rigorous cost-benefit analysis.* Nonetheless, if reliable data on estimated savings and false alarm costs were available, a cost-benefit analysis would indicate whether the net benefits (benefits minus costs) of the EWS were greater than zero. The benefits and costs would be composed of various factors, as indicated in Figure 6.1.

The costs per user include the system capital costs amortized over the system lifetime, operating costs, and the false alarm costs given by survey respondents, weighted by the annual occurrence of false alarms. The benefits per user are the estimated savings or avoided losses given by survey respondents, weighted by the probability of a damaging earthquake for which a warning could be issued. Since the annual probabilities of an earthquake and of false alarms are presumed to be uniform over time, our analysis focuses on the expected net benefits in a given year t. When the system costs are amortized over the system lifetime, the net benefit in year t will accurately represent the net benefit of an EWS over its system lifetime.

As detailed in Chapter Four, the survey respondents' desire for long warning times (greater than 30 seconds) suggests that a warning system would be useful (in the Los Angeles metropolitan area) only for large (M7.5 or greater) events on the San Andreas fault. The annual probability of such an event has recently been estimated by the United States Geological Survey as about 2 percent. These estimates are based on earthquake recurrence models which consider the slip rate of the fault and the time of the last characteristic event. To the extent that these models accurately represent the characteristic events of the southern San Andreas fault, the estimated annual probabilities are reasonable.

The actual annual benefits of an EWS should be less than the estimated savings anticipated by potential users weighted by the 2 percent annual probability of the event occurring because the probability of actual damage to a facility is less than the probability of the event occurring. Moreover, the 2 percent annual probability of an event on the southern San Andreas fault is a combination of the probabilities associated with ruptures on the Coachella and Mojave segments of the fault. If only the Coachella segment ruptures, however, little damage may result in the Los Angeles Basin.

As indicated in Chapter Four, the system capital costs range from $3.3 million to $5.8 million and the annual operating costs range from $1.6 million to $2.4 million. When the system capital costs are amortized over a 25-year period (the assumed system lifetime) at a real interest rate of 4.0 percent (the long-term U.S. Treasury securities rate minus current rate of inflation–9% - 5%), the annualized capital costs range from $211,000 to $369,000. Adding in the estimated annual operating costs, the total annual system costs range from $1.8 million to $2.8 million.

The expected annual occurrence of false alarms for a southern San Andreas fault-based EWS ranges from one false alarm every five years (0.2 per year) to once per year. These estimates are based on the experience of Japan Railways, adjusted for differences between Japanese and California seismicity (see Appendix B), and on the occurrence of M5.5 and greater earthquakes in the vicinity of the southern San Andreas fault.

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**Figure 6.1**

**Cost-Benefit Analysis Equations for Earthquake Warning System Analysis**

**General Cost/Benefit Equation:**

Net Benefits = Benefits - Costs

**Cost/Benefit of an EWS to an Individual firm in a given year t.**

Benefits(t) = Annual probability of a damaging earthquake **X** Estimated savings if warned

Costs(t) = (Capital costs per user + Operating costs per user) + (Annual occurrence of false alarms **X** Cost of a false alarm)

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## Decision Analysis

Despite the fact that the great uncertainty in the survey data prevents a formal cost-benefit analysis, decision rules may be derived upon which the economic feasibility an EWS can be based. These rules allow policy makers to discern the choices that are implied by an EWS, based on the economic and seismological characteristics. The decision rules may be derived as follows:

Given the EWS cost-benefit equation for all EWS users:

$$\text{Net Benefits} = p_{eq} \times B_w - [(C_s + C_o) + (p_{fa} \times C_{fa})]$$

Where: $p_{eq}$ = Annual probability of a damaging earthquake

$B_w$ = Estimated savings if warned

$C_s$ = Amortized annual capital costs of system

$C_o$ = Annual operating costs of system

$p_{fa}$ = Rate of occurrence of a false positive alarm

$C_{fa}$ = Cost of a false positive alarm

When Net Benefits = 0, Benefits = Costs.

Given $p_{eq}$ = 0.02 (annual probability of M7.5 event)

$p_{fa}$ = 0.20 (estimate of annual rate of false alarm),

then the one-time estimated savings for an EWS to break even, if a warning is issued, is given by

$$B_w = 50(C_s + C_o) + 10C_{fa}$$

The decision rules for a cost-beneficial EWS (benefits ≥ costs) under different scenarios can be stated as follows:

*I.* *If the system's costs (capital and operating) to users are set equal to 0 (i.e., if users do not pay the cost of the system), then the estimated savings must be at least 10 times the false alarm costs for the EWS to be cost-beneficial to users.*

For example, if the total false alarm costs are $1,000,000 then the total estimated savings from all users must be at least $10 million (10 X 1,000,000). (Although the system cost may be equal to 0 for users, these costs will have to be borne by some other entity.)

*II.* *If false alarm costs to users are set equal to 0, the total estimated savings must be at least 50 times the total annual system costs (capital and operating) for the EWS to be cost-beneficial.*

For example, if the total annual system costs are $1.8 million then the total estimated savings from all users must be at least $90 million (50 X 1.8 million).

*III.* *In the general case, the total estimated savings must at least 50 times the total system costs plus 10 times the total false alarm costs.*

These rules apply only with an annual earthquake probability of 2 percent and a system which issues false alarms at a rate of 0.2 per year (once every five years). This latter rate is the estimate of false alarms based on the anticipated average number of alarm-triggering earthquakes each year. This estimate does not include any possible system detection or communication false alarms. Taking into account instrument and communication malfunctions, the system could issue as many as one (1.0) false alarm per year.

Decision Rule III may be generalized as follows to account for variations in probability of an earthquake and the false alarm rate:

$$B_w = 1/p_{eq}\,(C_s+C_o) + (p_{fa}/p_{eq})\,C_{fa}$$

Thus, if the annual false alarm rate ($p_{fa}$) is 1.0 and the annual probability of a damaging earthquake ($p_{eq}$) is 0.02, then the multiplier on false alarm costs will be 50. Under these circumstances, estimated savings ($B_w$) must be at least 50 times the annual system costs *plus* 50 times the expected false alarm costs. For example, if system number 3 in Table 6.2 issues one false alarm per year and the total costs of such alarms (among all EWS users) are $10 million, the warning system would have to be capable of generating approximately $640 million in estimated savings or avoided losses, as shown in the last row of the table.

Table 6.2 also demonstrates the total level of savings that must accrue to all EWS users when an earthquake warning is issued, given various assumptions about the probability of an earthquake, system costs, false alarms, and false alarm costs. The annual probability of an earthquake (M7.5 and greater) is 2 percent. The annual false alarm rates are 0.2, 0.5, and 1.0. The assumed false alarm costs are $1 million, $5 million, and $10 million. These arbitrary false alarm costs illustrate how various false alarm costs affect the analysis. The top and middle sets of data (A and B) show the savings that an EWS must generate if (1) there are no system costs to users, and (2) there are no false alarm costs. The bottom set of data (C) represents a reasonable scenario; that is, the system and false alarm costs are nonzero.

As is shown in Table 6.2, the necessary savings for an EWS to be cost-beneficial increases dramatically as the annual number of false alarms rises. Even if there were no false alarm costs, the required savings would have to exceed $91 million. Of course, false alarms will occur with any complex system. Under the best of conditions (false alarm rate = 0.20), a basic EWS covering only the southern San Andreas fault would have to provide at least $101 million in estimated savings or avoided losses to be cost-beneficial. The most reasonable scenario (represented by set C in Table 6.2) indicates that the estimated savings necessary to support an EWS which breaks even ranges from $101 million to $640 million. Thus, depending on the system costs and the actual level of false alarm costs and frequency, a cost-beneficial EWS would, based on this analysis, have to result in hundreds of millions of dollars in estimated savings.

### Effect of a Reduction in Casualties as a Result of an EWS

The net benefit of an EWS could be substantial if the system could, in fact, reduce injuries and the loss of life. Although we cannot estimate how many casualties could be avoided if an earthquake warning were issued, we can document the values that the California legal system has assigned (in settlements and court awards) to death, loss of limb and eyesight in recent years. Of course, settlements and awards theoretically depend on many factors, including the age, earnings, and occupation of the victim, as well as costs that occur prior to or as a result of the death or injury. And, in the case of awards, there are punitive or deterrent awards given to plaintiffs. Given these limitations, settlements and court awards nonetheless represent how the California legal system assigns value to casualties. If an EWS were operable and casualties were reduced/increased as a result of responding to a warning, these amounts may be reasonable estimates of the values involved if settlements or awards are reduced or increased.

## Table 6.2

### Estimated Savings Necessary to Make EWS Cost-Beneficial under Various Earthquake Warning System Configurations

| System Number | Calculated Savings If EWS Is To Be Cost-Beneficial | Annual Probability of Earthquake | Annual System Costs to Users | Number of False Alarms per Year | Costs if False Alarm Occurs |
|---|---|---|---|---|---|
| A. Users Experience No System Costs, Incur False Alarm Costs | | | | | |
| 1 | $10,000,000 | 0.02 | $0 | 0.20 | $1,000,000 |
| 1 | 25,000,000 | 0.02 | 0 | 0.50 | 1,000,000 |
| 1 | 50,000,000 | 0.02 | 0 | 1.00 | 1,000,000 |
| 2 | 50,000,000 | 0.02 | 0 | 0.20 | 5,000,000 |
| 2 | 125,000,000 | 0.02 | 0 | 0.50 | 5,000,000 |
| 2 | 250,000,000 | 0.02 | 0 | 1.00 | 5,000,000 |
| 3 | 100,000,000 | 0.02 | 0 | 0.20 | 10,000,000 |
| 3 | 250,000,000 | 0.02 | 0 | 0.50 | 10,000,000 |
| 3 | 500,000,000 | 0.02 | 0 | 1.00 | 10,000,000 |
| B. Users Experience No False Alarm Costs, Incur System Costs | | | | | |
| 1 | 91,080,000 | 0.02 | 1,821,600 | 0.20 | 0 |
| 1 | 91,080,000 | 0.02 | 1,821,600 | 0.50 | 0 |
| 1 | 91,080,000 | 0.02 | 1,821,600 | 1.00 | 0 |
| 2 | 122,825,000 | 0.02 | 2,456,500 | 0.20 | 0 |
| 2 | 122,825,000 | 0.02 | 2,456,500 | 0.50 | 0 |
| 2 | 122,825,000 | 0.02 | 2,456,500 | 1.00 | 0 |
| 3 | 139,620,000 | 0.02 | 2,792,400 | 0.20 | 0 |
| 3 | 139,620,000 | 0.02 | 2,792,400 | 0.50 | 0 |
| 3 | 139,620,000 | 0.02 | 2,792,400 | 1.00 | 0 |
| C. Users Experience System and False Alarm Costs | | | | | |
| 1 | 101,080,000 | 0.02 | 1,821,600 | 0.20 | 1,000,000 |
| 1 | 116,080,000 | 0.02 | 1,821,600 | 0.50 | 1,000,000 |
| 1 | 141,080,000 | 0.02 | 1,821,600 | 1.00 | 1,000,000 |
| 2 | 172,825,000 | 0.02 | 2,456,500 | 0.20 | 5,000,000 |
| 2 | 247,825,000 | 0.02 | 2,456,500 | 0.50 | 5,000,000 |
| 2 | 372,825,000 | 0.02 | 2,456,500 | 1.00 | 5,000,000 |
| 3 | 239,620,000 | 0.02 | 2,792,400 | 0.20 | 10,000,000 |
| 3 | 389,620,000 | 0.02 | 2,792,400 | 0.50 | 10,000,000 |
| 3 | 639,620,000 | 0.02 | 2,792,400 | 1.00 | 10,000,000 |

Notes: System number 1 includes 43 instruments along the southern San Andreas fault at a capital cost of $3,290,000 (amortized annual costs = $210,600) and annual operating costs of $1,611,000.

System number 2 includes 110 instruments in the Los Angeles Basin at a capital cost of $4,351,000 (amortized annual costs = $278,500) and annual operating costs of $2,178,000.

System number 3 includes 153 instruments along the southern San Andreas fault and in the Los Angeles Basin at a capital cost of $5,771,000 (amortized annual costs = $369,400) and annual operating costs of $2,423,000.

We reviewed 84 cases before courts in California in the past three years. These settlements or court awards for wrongful death or injury were settled or awarded in favor of the defendants. The defendants were gainfully employed, between the ages of 18 and 65 and included both sexes. Of the 84 cases, 62 involved wrongful death and 22 involved loss of limb (20) or eyesight (2).

### Death Settlements and Awards

Of the wrongful death cases, 87 percent involved male victims listing a wide range of occupations, including construction worker, attorney, waiter, engineer, sales, and others. One-half of these 62 cases were settled or awarded in three counties–Los Angeles (21), San Francisco (6), and San Bernardino (4). The other one-half of the cases were resolved in various other counties.

Twenty-four (24) of the wrongful death cases were settled for a mean amount of $861,000. These settlements ranged from $100,000 to $4 million. The remaining 38 cases that were resolved in court resulted in a mean award of $830,000. The awards ranged from $25,000 to nearly $5 million. We conclude that, in general, the California legal system in recent years has assigned the average value of approximately $900,000 for the loss of life. (This amount is similar to the result of a study by the Rand Corporation of the economic losses suffered by survivors of aircraft disaster victims where an average loss was calculated to be $749,000.)

### Injury Settlements and Awards

Among the injury cases, 87 percent involved male victims listing various occupations such as laborer, certified public accountant, waiter, seaman, chiropractor, and others. Approximately one-half of these 22 cases were settled in Los Angeles (6), San Francisco (4), and Fresno (2) counties. The balance were resolved in various other counties.

Twelve (12) of the injury cases were settled for a mean amount of $753,000. Ten cases were resolved in court for a mean award of $1,168,000. Settlements ranged from $200,000 to $1.8 million. Court awards ranged from $60,000 to $3.2 million. If we accept the data centers as reasonable estimates of average settlements or awards, the California legal system in recent years has assigned an average value of approximately $1 million for the loss of limb or eyesight.

It is not clear why injury settlements and awards in California are greater than settlements and awards in wrongful death cases. Such a result may reflect (1) the additional cost of providing income and medical support for the injured throughout their lifetime, and/or (2) a sympathetic response juries may have for injured persons who appear in court.

### Implications of Death/Injury Value Estimates on EWS Benefits

If an EWS were proposed only to save lives or reduce injuries–not reduce loss of property–the system would still have to perform demonstrably to justify its operation. *Based on our review of the values that result from legal action in California* *involving the loss of life, limb, and eyesight, at least 100 such casualties would have to be avoided when a warning is ultimately issued to generate the amount of savings for a basic EWS to be a cost-beneficial measure of reducing casualties.* Of course, injuries or death could occur as a result of responding (appropriately or inappropriately) to an earthquake warning. Thus, the EWS must be able to demonstrate a *net* reduction in casualties.

To further address the question of the applicability of an EWS in reducing injuries or loss of life, we reviewed data on occupant behavior compiled by Michael E. Durkin and Associates, an earthquake response consulting firm. Although an EWS could allow occupants to take protective actions such as getting under a desk or standing in a doorway, attempts to evacuate the building can have dangerous results. Occupant response studies by Durkin and others show that building occupants frequently attempt to evacuate buildings, even buildings not in danger of collapse, when the shaking starts. Spontaneous evacuations of high-rise buildings have occurred even when the emergency plan specifies other protective action. Based on experience from the 1983 Coalinga earthquake, more injuries occurred to those who exited buildings than to those who remained inside. In the 1933 Long Beach earthquakes, most fatalities occurred outside and adjacent to unreinforced masonry buildings. Evacuations of buildings prompted by an earthquake warning, therefore, could result in a greater number of injuries from falling debris in stairwells and adjacent to buildings than if personnel remained inside the facility until the shaking ceased.

Based on earthquake experience data, the value of general personnel safety uses of an EWS are ambiguous. An EWS used for such purposes may, in fact, result in greater casualties. On the other hand, as we have indicated elsewhere in this report, there are personnel safety uses that would be beneficial (workers getting away from hazardous equipment or areas prior to shaking). General building uses would have to be carefully evaluated on a case-by-case basis before they are proposed. In any case, the personnel safety uses of an EWS, by themselves, do not appear to modify the basic conclusion that tangible and demonstrable savings must be shown before investment in an EWS is justified as cost-beneficial.

### Summary and Conclusions

The estimated savings and false alarm cost data from the survey results contain too much variability to be used in a rigorous cost-benefit analysis. Given the probability of damaging, warnable earthquakes and the expected rate of false alarms, the system must demonstrate outstanding benefits to compensate for the system and false alarm costs. The relationship between the system costs, estimated savings, and false alarm costs may be summarized by the following decision rules:

- If users do not pay for any of the capital and operating costs of the system, the expected estimated savings must be between 10 and 50 times the expected false alarm costs for the EWS to be cost-beneficial to the users.
- If there are no false alarm costs, the total estimated savings must

be at least 50 times the total annual system costs for the EWS to be cost-beneficial (to compensate for the capital and operating/maintenance costs).

If the users do pay the system costs and there are false alarm costs, then the total estimated savings must be at least 50 times the total system costs plus 10 to 50 times the total false alarm costs to be cost-beneficial.

These rules assume that the annual probability of a M7.5 or greater earthquake is 2 percent and that false alarms will occur between 0.2 and 1.0 times per year.)

Thus, for an EWS to be cost-beneficial, there should be outstanding estimated savings–tens to hundreds of millions of dollars–associated with its use. In addition, these savings should be substantially greater (10 to 50 times) than the costs of responding to a false alarm. Finally, the system should be reliable–that is, the system must work when a damaging earthquake occurs. These conclusions reveal that if an EWS is to be feasible, it should be implemented for those uses that are of high enough economic value to pay for the significant system costs and offset any possible false alarm consequences and reliability difficulties.

# Chapter Seven–Funding and Management

## General Considerations

As outlined in Chapter Six, the capital costs for such a system would range from $3.3 million for a system which covers only the southern San Andreas fault to $5.8 million for a system which covers the southern San Andreas fault plus the entire Los Angeles Basin. The annual operating and maintenance costs would range from $1.6 million to $2.4 million and include 8.0 to 11.0 personnel-years in staffing, respectively. The organizational and funding arrangements that are necessary to support these system options are discussed in this chapter as operating and financing options. Rather than present detailed plans for operating and financing such systems, we discuss the various arrangements under which an EWS could be operated/financed. If such a system were authorized and funded, a detailed operations plan would have to be developed, discussing matters such as round-the-clock staffing, a schedule for implementation, and arrangements with subscribers of an EWS.

There are various operating and financing options for an EWS. The system could be operated by a public entity, a private organization, or a public-private partnership. In general, the financing of an EWS depends on who builds and operates the system; that is, a publicly operated system is likely to be funded by public monies. Because of the considerable uncertainty as to the public benefit of an EWS, our discussion emphasizes the general organization and financing of an EWS, rather than recommending a specific system.

There are several considerations that must be taken into account in deciding how an EWS will be operated and funded. These considerations include:

- **Purpose and scope of an earthquake warning system.** An EWS could provide warnings for personnel safety, protection of vulnerable systems or equipment, or public safety. If the purpose of developing an earthquake warning system is to improve general public safety, then a system which is State owned and operated may provide for greater accountability. If, instead, the purpose is to encourage private organizations to develop earthquake alarm capabilities, then a privately-operated system may be preferable, with the State providing incentives for development. Similarly, the scope of an EWS can be based on either providing (1) a general warning to all potentially at-risk areas throughout the state, or (2) a limited warning to certain groups. A general warning EWS might best be organized and funded by public entities while a limited warning EWS is probably better left to those organizations that will benefit from the system. Thus, the organization and financing of an EWS should be based on the specific purpose of the system and the geographical areas and uses that the system is to reach.

- **Appropriate government role.** The appropriate role of the government in developing an EWS is derived from the purpose of the system. If the system is to be for public safety, it may be preferable for the government to be directly involved in the EWS development and operations. If the system is to provide an alarm system that is limited to certain individuals or private organizations, the appropriate role for government may be to set standards and regulate the system so that consumers are protected and public safety is ensured.

- **Anticipated beneficiaries of an EWS.** The question of who benefits from an EWS also influences the organization and financing of a system. If, for example, an EWS profoundly benefits a narrow group of users, it may be more appropriate for those users to collectively develop, operate, and finance the system. If, however, there is a clear benefit to the greater public from an EWS, then a publicly operated and financed system may be appropriate.

- **Availability of funding.** The availability of funding is critical to the operation and financing of an EWS. A project may have an outstanding public benefit but, because of restrictions or limitations on public funding, may not warrant consideration over higher priority publicly-funded projects. In this case, decision makers may want to consider private financing or public funding sources that are less restricted (such as user fees).

- **Exposure to liability.** The arrangements for operating and financing an EWS may result in exposure to liability by public entities and employees. Thus, the organization of a proposed EWS should balance the liability considerations of various operating and financing options with the other organizational considerations.

The first section of this chapter discusses various operating and financing options for an EWS, including systems that are publicly operated, privately operated, and blended operations. In the next section, we discuss the general operating and financing characteristics of these systems. Finally, the potential funding sources for an EWS are presented.

## EWS Operating and Financing Options

### Publicly Owned and Operated Systems

**State EWS.** A State operated EWS should be located in a department which has the seismological expertise to operate the system and correctly interpret its results. In addition, the agency should be able to perform emergency information functions, such as providing information to the news media and the public. The State agencies which have responsibilities for earthquake information and response are listed.

- The Department of Conservation's Division of Mines and Geology (DMG) includes 46 personnel who work in the Hazards Reduction and Strong Motion Instrumentation Program and employs approximately six seismologists who develop and provide information on earthquakes, earthquake history, earthquake planning scenarios, and analyses of earthquake hazards. The DMG is the State's seismological representative on the United States Geological Survey's

Parkfield Prediction Experiment. The DMG also provides information to the public and news media.

- The Department of Water Resources (DWR) collects seismological data for its use in operating the State Water Project. The Earthquake Engineering Section staff at DWR includes 4.0 personnel-years and two seismologists. When an earthquake occurs, location data from the DWR's seismic network is forwarded to the Governor's Office of Emergency Services for its use in emergency response and public information.

- The Governor's Office of Emergency Services (OES) coordinates emergency activities necessary to save lives and reduce losses from natural or other disasters. As part of its charge, the OES provides emergency information on fires, floods, earthquakes, hazardous materials and other emergencies statewide. The OES uses the seismological expertise of the DWR and DMG.

- The University of California at Berkeley operates the Berkeley Seismographic Station, which monitors and analyzes earthquake activity statewide and provides information to the news media and public. The Station employs 18 personnel, four of whom are seismologists.

Based on the need to have both in-house seismological expertise and emergency information capabilities, the DMG is probably the best suited State organization to operate an EWS.

**Regional EWS.** Another publicly owned and operated EWS option would be a Regional EWS, operated by a regional organization such as Los Angeles County, the Southern California Association of Governments, or the Association of Bay Area Governments. Under this arrangement, a regional organization would establish its own in-house seismological expertise and develop its own warning network. The advantage of the regional approach is that the areas subject to the greatest risk would take responsibility for the operation and financing of an EWS. Low risk areas of the state would therefore not be required to underwrite the cost of a system which confers benefits on other parts of the state.

**Privately Owned/Operated Systems**

A private EWS would operate under a different set of principles. First of all, the public benefit of the system is not likely to be the motive for which investors would undertake the development and operation of an EWS. To be viable, a private EWS would have to sell to a hypothetical market for earthquake warning. The market might include customers from residential, commercial, and industrial classes but would have to comprise enough users that are willing to pay for the cost of the system plus a return on the investment. Based on the survey results, it is not clear whether there are enough potential customers to warrant the private development of such a system. In the course of this study, we have come across two organizations that are considering the development of a private system. If, in fact, a private approach to earthquake warning is viable, government development may not be necessary.

### Other Arrangements

In addition to the public and private options of operating and financing an EWS, a system could be organized in at least two other ways. A private organization could supply the equipment and maintenance for an EWS, thus sparing the State or regional agency the costs and risks associated with building the system. The cost of the system would be financed by public monies in much the same way as if it were a publicly owned and operated system. As part of such an arrangement, the public entity could require the private party to indemnify the State for legal fees and damages resulting from an equipment failure.

The public entity could also develop and construct an EWS and then contract with a private organization to operate the system. In this case, the public entity could competitively bid the project on a regular basis in an attempt to hold down the operating costs of the system. The public entity could require the contractor to indemnify the State or regional agency for legal fees and damages resulting from operations.

## Availability of Funding for an EWS

Funding for an EWS will be based on the ultimate organization of the system. The possible fund sources that could support such a system include federal, regional and private financing, including a system of user fees.

### Federal Funds

**National Earthquake Hazards Reduction Program.** The National Earthquake Hazards Reduction Program (NEHRP), coordinated by the Federal Emergency Management Agency (FEMA), was established by Congress in 1977 to reduce the risk to life and property from earthquake hazards. NEHRP is composed of five major elements: Hazard Delineation and Assessment; Earthquake Prediction Research; Seismic Design and Engineering Research; Preparedness Planning and Hazard Awareness; and Fundamental Seismological Studies. The 1988 federal fiscal year (FFY) expenditures for all NEHRP activities are estimated to be $64.6 million.

Under NEHRP, funding is allocated to FEMA for lead agency activities, earthquake planning and hazard reduction, postearthquake studies, and preparation of information materials. In FFY 1988, FEMA is expected to spend $5.9 million for these programs. FEMA allocates a portion of its NEHRP funding to the states for preparedness planning and hazard awareness activities. The California Office of Emergency Services received $771,000 from the FEMA state and local grants program for FFY 1989 (beginning October 1988) for emergency preparedness and earthquake response planning activities. Most of FEMA funding allocated to California goes to the Bay Area Regional Earthquake Preparedness Project and the Southern California Earthquake Preparedness Project. FEMA's state and local grants program is an unlikely source of funds for an EWS.

The United States Geological Survey (USGS) receives funding for earthquake potential and hazard assessments, earthquake prediction and engineering research, information systems, postearthquake studies, and international cooperation. In FFY 1988, NEHRP expenditures by the USGS are estimated to be $32.7 million. The National Science Foundation is responsible for earthquake engineering research, planning and mitigation, information systems, postearthquake studies, international cooperation, and studies of plate tectonics and earthquake processes. The FFY 1988 expenditures by National Science Foundation for NEHRP activities are an estimated $25.4 million. The National Institute for Standards and Technology (formerly the National Bureau of Standards) expenditures for engineering research, postearthquake studies, and international cooperation in FFY 1988 are an estimated $525,000.

NEHRP funding allocated to earthquake research and engineering activities in the National Science Foundation and the USGS may be available (at least in part) for the development and operation of an EWS. Funding for a California EWS, however, would have to compete with projects throughout the United States. Federal participation in a California EWS project would have applications to other parts of the United States. Because the attenuation of strong motion is much less in the middle and eastern United States, a recurrence of the New Madrid, Missouri earthquakes of 1811 and 1812 (three events of M8 and greater) could result in much larger warning areas.

**National Research Council Activities.** In December 1987, the National Research Council (NRC) organized a Panel on Real-Time Earthquake Warning to study various aspects of real-time earthquake detection and warning systems. The panel is composed of public and private representatives from seismology, engineering, and emergency response. The panel is to report on their findings in early 1990. Although the panel is only charged with studying real-time seismology, the NRC's interest in funding this study reflects a national interest in this subject.

### Regional Funding

A regional EWS could be financed by general funds (property tax and sales tax revenues), general obligation and revenue bonds, and user fees (levied against local governments and private organizations). Local funding, however, is also subject to the State Appropriations Limit discussed above. Thus, funding for a Regional EWS would depend on the locality as well as the funding arrangements. If a Regional EWS were mandated by chaptered legislation, the regional authority could make a case (under provisions in the State Constitution regarding State-mandated costs) to receive reimbursements from the State.

**Financing by User Fees.** State or local government operation of an EWS could be financed by user fees based on the number of users and the relative value of the warning to each user. User fee revenues which reflect the reasonable costs of providing a warning would not be subject to the State Appropriations Limit governing State and local government expenditures. Thus, the program would not compete with other programs for funding or space within the appropriations limit. As a practical matter, setting fees based on the cost of service would result in overcharges to some users (relative to the value of the system to the user) and undercharging others. Under these circumstances, those with expected savings less than the subscription costs would probably not subscribe to the EWS, thus raising the subscription price for others. Moreover, potential users may be reluctant to subscribe to an EWS before it has been proven to be reliable and effective. The survey results indicated some interest in paying a subscription price for an EWS. It is not clear, however, whether such subscriptions could, in fact, support the capital and operating costs of an EWS.

### Private Financing

The financing of a private system requires funding for the capital costs to install the system and annual operating costs. Presumably, a private operation would be supported by a service fee to subscribers. These fees would have to pay for the total costs as well as a return on investment. Based on the systems analyzed in Chapters Four and Five, the total annual subscription amounts would have to generate between $1.8 million and $2.8 million, plus a return on investment. As we indicated earlier, two private organizations have investigated or are investigating the business potential of an EWS, including its use in warning residences. Because this study focuses on the benefit that an EWS provides to public and private organizational facilities, we cannot estimate the acceptance or potential benefit that an EWS may have for residential subscribers. In fact, because of the greater base of customers, an EWS for residential use may have commercial potential. If so, the private operation and financing of an EWS may be feasible.

Financing for a private system might be encouraged by a grant of immunity from liability by the State in return for service to the State or based on a sale of warning rights. Under such an arrangement, however, the State would want to ensure that the EWS developer meets specified performance criteria.

## Conclusions

The organization of an EWS should be based on the following considerations: the purpose of an EWS, the appropriate role of government based on the expressed purpose, the anticipated beneficiaries of an EWS, funding availability, and exposure to liability. There is no preferred organizational arrangement for an EWS. Such a system could be operated by State or regional government by a private enterprise. Federal funding may be available to support the development and operation of an EWS under the auspices of the National Earthquake Hazards Reduction Program. Because of limited funding availability and competing needs, State and local governments may not be able to support the financing of an EWS. The viability of a private operation will probably depend on the (1) reliability and effectiveness of the EWS, and (2) development of an extensive market to justify the large capital and operating costs of an EWS.

# Chapter Eight–Liability Issues

Chapter 1492 specifies that the earthquake warning system feasibility study include a description of the "liability aspects of the system." The liability considerations for an EWS are important because the issuance of a warning can have important economic consequences. Damages, injuries and a loss of productive capacity can result from responding to either true or false alarms. Thus, the liability issues concerning an earthquake warning system are critical when considering its feasibility.

In order to provide an analysis of the liability issues of earthquake warning, the specific questions relevant to the implementation of an EWS were first identified, based on a review of the legal literature regarding earthquake warning. Next, these questions were reviewed with individuals familiar with legal issues of earthquake mitigation. Finally, the resulting set of questions, along with background information regarding an EWS, were submitted to the California Attorney General and, under the auspices of President pro Temporare of the Senate, the Legislative Counsel for a legal analysis.

### Background

Historically, the tort liability of government has been regulated by the doctrine of sovereign immunity. Sovereign immunity is derived from the English common law immunities of the King and, simply put, holds that the government can only be sued with its permission. The doctrine of sovereign immunity has evolved to include two types of duties incumbent on the government. Duties which the government are obligated by statute or ordinance to perform are *mandatory* duties and the failure to exercise these duties results in government liability. Duties which the government are not specifically obligated to perform are *discretionary* duties. In general, government is not liable for acting or failing to act when a duty is discretionary. California statutory law relating to government liability, and mandatory and discretionary duties are specifically addressed in the California Tort Claims and Emergency Services Acts.

### California Tort Claims Act

The Tort Claims Act specifies that government tort liability is governed by statute. Thus, government immunity from liability is the rule unless liability is imposed by statute. A public entity is liable for an injury if it fails to discharge a mandatory duty imposed by an enactment of a statute or ordinance. A public employee, however, is not liable for injury resulting from an act or omission if the act or omission is (1) the result of exercising discretion, regardless of the consequences, and (2) *not* ministerial–that is, the act or omission is undertaken by a person with general policy making responsibilities, such as a chief executive or cabinet officer. Ministerial acts, however, are not immune from liability if the acts or omissions are negligently performed. Finally, under this Act, public entities are not generally liable for an injury resulting from an act or omission of its employees if the employee is immune from liability.

A portion of the Act specifically addresses earthquake prediction warnings. Government Code Section 955.1 permits the Governor to issue a warning of an *earthquake prediction*. In addition, Section 955.1 provides specific immunity to public officials involved in the development and issuance of an earthquake warning. Finally, Section 955.1 declares that an earthquake warning issued by the Governor is sufficient basis for a declaration of a state of emergency or local emergency as defined in the California Emergency Services Act.

**California Emergency Services Act**

The Emergency Services Act authorizes preparedness (1) for emergencies that imperil the lives, property, and the resources of the State, and (2) that protects the health and safety and preserves the lives and property of the people of the State. The Act specifies three types of emergencies and the procedures under which these emergencies may be proclaimed. Under the Act, public entities and their employees are not liable for performance or nonperformance of discretionary acts or duties in an emergency.

## Specific Liability Questions and Responses

The questions relating to the liability considerations of an EWS may be grouped into the following categories:

- Authority to issue an earthquake warning.
- Liability of the State under various conditions, and
- Changes in existing law necessary to enable an EWS.

To address the issues in each of these categories, specific questions were developed and submitted to the Attorney General and the Legislative Counsel for a formal legal opinion. The Attorney General responded to our request for opinion by providing a legal analysis, indicating that the lengthy review process necessary for a *formal legal opinion* precluded such a response to our request. Nonetheless, the Attorney General's response to our inquiry represents the professional analysis and judgment of the Attorney General, the State's legal representative in matters of State liability. The Legislative Counsel is the Legislature's attorney and is consulted on legal and policy matters of particular interest to the Legislature.

For brevity, the specific questions and responses have been paraphrased. The Legislative Counsel's opinion is included where it differs from or adds to the Attorney General's analysis.

**Authority to Issue an Earthquake Warning**

**Question:** Does Government Code Section 955.1 (governing earthquake *prediction* warnings), the California Emergency Services Act, or other provisions of existing California law permit the issuance of an earthquake warning by State employees or officials? Also, can the Governor delegate the authority to issue an earthquake warning to State employees or officials?

**Response:** The statutory authority to issue an earthquake warning is reserved exclusively for the

Governor. The Attorney General indicates that general propositions of law provide that the Governor can delegate authority through an executive order. Government Code Section 955.1 neither allows for nor prohibits the delegation of authority, although the section does not specifically permit or prohibit State civil service employees or other officials from issuing an earthquake warning. Public entities and employees are only immune from liability for actions taken in response to an earthquake warning, however, if the warning was issued pursuant to the Governor's authority under Section 955.1. If the Legislature authorizes an EWS, the Attorney General recommends that the Governor's authority be clarified by statute.

The Legislative Counsel indicates that the delegation of authority may not be desirable for policy reasons, but that, in any case, such authority could not be delegated.

**Liability to State if End Users Voluntarily Subscribe**

**Question:** Is the State or are State employees liable for damages/injuries to end users of a State-operated EWS if (1) the end users voluntarily subscribe to the EWS, and/or (2) the State EWS operator advises end users of specific performance criteria expected of an EWS?

**Response:** The Attorney General indicates that if an end-user voluntarily contracts for the services of an EWS with the expressed understanding that the system is experimental and subject to a possible interruption of service, it is not likely that the State or its employees will be liable for damages/injuries from an end user's response–even if the EWS fails to meet specific performance criteria.

**Liability if EWS Is State-Operated**

**Question:** Is the State or are State employees liable for damages/injuries resulting if a State-operated EWS (1) does not issue a warning when an earthquake occurs, (2) issues a warning when no earthquake occurs, and (3) issues a warning appropriately, but damages/injuries nonetheless result?

**Response:** The Attorney General indicates that it is unlikely that liability will attach to the State or its employees for any warning errors or resulting damages arising from State-operation of an EWS. Public entities and employees might be liable from the *negligent* dissemination of an EWS warning, however. In *Connelly v. State of California* (1970), the Court of Appeal held that liability may be predicated upon gathering, evaluating, and disseminating flood forecast data in a *negligent* manner. The Court reasoned that these activities are administrative or ministerial activities and not governed by the discretionary immunity of Government Code Section 820.2. Thus, dissemination of an earthquake warning in a negligent manner could result in liability to the State and State employees. As long as reasonable care is taken in compiling the data for public dissemination, however, liability will be limited. Damages or injuries to third parties (i.e., employees or visitors injured by the user's response to a warning) are not addressed in *Connelly* but it appears that the State would be liable for damages to third parties if the State was found to be negligent. The State can further reduce its exposure to liability through the use of contractual indemnification and defense provisions in a subscription contract.

The Legislative Counsel concurs that "liability would not be the result of an incorrect warning per se, but may arise because of the reasons the warning was incorrect."

### Liability to State if EWS Is Privately-Operated

**Question:** What is the liability to the State and State employees if the EWS is constructed/operated by a private operator (1) because the private operator independently initiates and implements an EWS based on the State's study results that indicate that such a system is feasible?, or (2) if there is a direct contractual agreement between the State and a private party to construct/operate an EWS?

**Response:** The Attorney General indicates that the mere existence of a study, or the conclusions or data contained therein, do not give rise to a duty to either proceed with an EWS or a duty to prevent private parties from proceeding with one. Private construction and operation would not appear to violate any statute and therefore would be a legal business endeavor which the State is not required to regulate.

The State may be held accountable, however, for the acts of a private operator under contract with the State. The State's exposure to liability, however, may be reduced if there is a clause in the contract requiring that the private operator indemnify and defend the State.

The Legislative Counsel adds that even if the State does not contractually require that the private contractor indemnify the State, there may be implied indemnity, since the contract itself implies a duty on the contractor to perform the work with due care.

### Liability to State if Existing Networks Are Accessed to Obtain/Issue Warnings

**Question:** What is the liability to the State and State employees if private parties connect to and utilize the State's existing seismic data network to provide themselves or third parties with an earthquake warning? Also, what would be the liability to the State and State employees if private parties connect to and utilize a State managed or operated EWS in order to provide an earthquake warning to third parties?

**Response:** According to the Attorney General, it is unlikely that the State will incur liability if private parties connect to the State's existing system or to an EWS to obtain an earthquake warning or to disseminate the warning to third parties. Allowing private parties access to either an existing seismic data network or to an EWS is directly analogous to the compilation and publishing of similar information in written form. Again, as long as reasonable care is taken in compiling the data for public dissemination, liability will not attach to the State.

### Liability for Indemnification of End Users if Damages/Injuries Occur

**Question:** Is the State liable for indemnifying end users of an EWS if damages/injuries are incurred by the end user's employees or third parties if the State-operated EWS (1) does not issue a warning when an earthquake occurs, (2) issues a warning when no earthquake occurs, and (3) issues an appropriate warning, but damages or injuries nonetheless result?

**Response:** The Attorney General indicates that there should be no liability for indemnification of end-users unless the State enters into an agreement to indemnify them. In fact, it may be wise for the State to indicate in promotional materials and require in contracts that end users indemnify and defend the State.

### Liability if EWS Is Not Implemented or Is Selectively Implemented

**Question:** Does the State have a duty (mandatory or discretionary) to implement an EWS if the feasibility study now underway finds that it is technically feasible or recommends that such a system be implemented?

**Response:** The Attorney General indicates that, in the absence of a statute or other enactment specifying a State obligation to implement an EWS, no mandatory duty exists. Thus, the decision to implement an EWS is discretionary.

The Legislative Counsel concurs that a decision to proceed would be an "exercise of discretion" and is therefore immune.

**Question:** On what basis can the State or State employees sequence or exclude the availability of an EWS to different classes of end users without incurring liability for damages/injuries?

**Response:** The Attorney General indicates that the State incurs no special liability by limiting or excluding the availability of an EWS to different classes of end-users, so long as such distinctions do not discriminate based on race, sex, handicap, religious, or sexual orientation.

**Question:** Would the State or State employees be liable for damages/injuries resulting from an earthquake which could have been theoretically mitigated if an EWS had been operable at the time of the earthquake?

**Response:** No. Because there is no mandatory duty to implement an EWS, the State will not be liable for damages/injuries which could have been theoretically mitigated or prevented by one.

### Liability for a Decline in Property Values or Income

**Question:** Would State or State employees or other non-State public entities or public employees be liable for a decline in property values or income as a result of the indirect effects of issuing an earthquake warning or placing instruments/equipment in a given area?

**Response:** The Attorney General indicates that there is generally no such liability associated with seismic hazard designation as long as due care is taken in preparing seismic hazard maps and information. Existing zoning regulations enforced by local governments use zones based on seismic hazards without incurring any special liability. Thus, it is unlikely that State or other public entities would be liable for the indirect effects resulting from the placement of instruments or issuance of warning in a given area.

## Changes in Existing Law Necessary to Enable an EWS

**Question:** What changes in existing law are necessary to (1) authorize the issuance of a earthquake warning by an EWS managed or operated by State employees or officials, (2) immunize public entities and employees (including the State and State employees) from liability in the event of an earthquake warning is issued by a State or privately managed/operated EWS, and (3) allow the State to indemnify the private operators of an EWS from damages/injuries to end users of an EWS as a result of issuing an earthquake warning?

**Response:** The Attorney General indicates that a specific statute may authorize the automatic or human issuance of an earthquake warning by an EWS operated by State employees or officials. In addition, the statute could immunize public entities and employees and contractors from liability associated with an EWS. In the absence of a specific statutory requirement, the State may contractually indemnify private operators of an EWS for damages to end users. Because of the potential costs involved, such a contractual provision would require legislative approval.

## Analysis and Conclusions

In general, the Attorney General's and Legislative Counsel's legal analyses indicate that the State implementation and operation of an EWS is not likely to be a source of significant liability to the State. This conclusion is conditioned on the following: (1) the limitations of the system are made known to end users, and (2) EWS employees exercise reasonable care in operating the system. A specific statute may authorize the issuance of an earthquake warning and provide immunity for public entities and employees involved in issuing the warning. The State may also limit liability from damages to end users of an EWS by including indemnification clauses in contracts with the end users.

If the State contracts with a private operator for an EWS, the State should require that the operator contractually indemnify and defend the State in court proceedings so as to limit the State's exposure. In addition, the private operator should be required to demonstrate financial solvency or that it has obtained a suitable insurance policy naming the State as an additional insured. If the State wishes to contractually indemnify a private operator from liability for damages to end users (so as to encourage private development of an EWS), the contractual provision would require legislative approval because of the potential costs involved.

In summary, the liability considerations of an EWS do not appear to be insurmountable barriers to the implementation of an EWS under current law. Contractual provisions between the State and private operators of an EWS or end users would appear to be sufficient to limit the State's exposure to liability. Exposure to the State could be further limited with the enactment of specific legislation authorizing warning and providing for specific immunities to the State and State employees.

# Chapter Nine–Conclusions

The conclusions of this study may be summarized as follows:

*Long warning times desired by survey respondents effectively limit the applicability of an EWS in southern California to the San Andreas fault.* Based on the results from two surveys, potential users generally desire warning times of 30 seconds or greater. An expert analysis of earthquake experience data corroborated the lack of short warning time uses. Thus, candidate earthquake faults for an EWS should be capable of generating a M7.5 or greater event. In southern California, earthquakes of M7.5 or greater would be limited, in all likelihood, to the southern San Andreas fault. The USGS estimates that the annual probability of such an event is 2.0 percent. If potential users required 10 seconds or greater of warning time, an EWS would still be effectively limited to covering faults capable of generating major earthquakes (M7 or greater).

*Local P-wave warning systems can provide warning times of a few seconds.* If very short warning times (10 seconds or less) become desirable, existing local P-wave warning system technology could provide the necessary information. A local P-wave system could supply longer average warning times (in the significantly damaged areas) than an EWS for earthquakes of approximately M6.5. Thus, existing technology and equipment is currently available which can furnish equivalent short warning capabilities.

*Potential users appear to be skeptical of the reliability of an EWS.* Even when survey respondents indicated a use for an EWS, they were reluctant to take the human decision maker out of the earthquake response process. The long warning times given by survey respondents are, perhaps, indicative of this skepticism. Based on our survey responses, it is unlikely that potential users would trust an EWS today to independently control vulnerable operations or equipment until it has proven its reliability and efficacy. Such skepticism is understandable given false alarm costs and unfamiliarity with a non-existing system. If an EWS were proven reliable, this skepticism might lessen.

*An EWS must provide tens to hundreds of millions of dollars in benefits and must perform reliably.* Because the estimated annual probabilities of major earthquakes in California are low, the expected savings/avoided losses must be large relative to the total annual costs (capital and operating) of the system. When certain system parameters (system costs, probability of a M7.5 earthquake, and the annual rate of false alarms) are considered, the results indicate that there must be tens to hundreds of millions of dollars in savings/avoided losses to justify investment in such a system. The annual cost to build (amortized over 25 years) and operate an EWS would range from $1.8 million to $2.8 million.

Based on our review, there is no compelling evidence that an EWS in California would produce such large benefits. It would not be, therefore, justifiable, on a cost-benefit basis, to construct an EWS at this time.

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# List of Appendices

# APPENDIX A

## CHAPTER 1492, STATUTES OF 1986, (SB 1238)

## AUTHORIZING THE EARTHQUAKE WARNING SYSTEM STUDY

Senate Bill No. 1238

## CHAPTER 1492

An act to amend Section 8690.4 of the Government Code, and to add Sections 2211 and 2804.6 to the Public Resources Code, relating to disaster relief, and making an appropriation therefor.

[Approved by Governor September 30, 1986. Filed with Secretary of State September 30, 1986.]

I am deleting the $200,000 appropriation from the Insurance Fund contained in Section 5.(b) of Senate Bill No. 1238.

The Insurance Fund does not have sufficient reserves to fund a study to evaluate an early warning system.

With this deletion, I approve Senate Bill No. 1238.

GEORGE DEUKMEJIAN, Governor

LEGISLATIVE COUNSEL'S DIGEST

SB 1238, Roberti. Earthquake.

(1) Under existing law, moneys in the 4 special accounts in the Natural Disaster Assistance Fund may be used for specified disaster relief purposes.

This bill would require the Controller to establish the Earthquake Emergency Investigations Account in that fund and would authorize the Seismic Safety Commission to allocate moneys from the account for specified earthquake investigation purposes.

The bill would require $100,000 to be transferred from the General Fund to the account and would appropriate the $100,000 from the account to the commission for allocation for the purposes of the bill.

(2) Existing law requires the Department of Conservation to develop jointly with the United States Geological Survey a prototype earthquake prediction system along the central San Andreas Fault near the City of Parkfield. The Office of Emergency Services, in consultation with the California Earthquake Prediction Evaluation Council, is required to develop a comprehensive emergency response plan for short-term earthquake prediction.

This bill would state that the department is the primary state agency responsible for geologic hazard review and investigation. The bill would also require the department, in consultation with the Seismic Safety Commission, to conduct a feasibility study evaluating the effectiveness of an early warning system to detect seismic activity along the San Andreas Fault north of the Los Angeles metropolitan area. The bill would appropriate $200,000 from the Insurance Fund to the department for the feasibility study.

Appropriation: yes.

*The people of the State of California do enact as follows:*

SECTION 1. The Legislature finds and declares that there is a strong likelihood of a major earthquake occurring in California before the year 2000 and, in order to better predict building failure and other life-threatening damage during an earthquake, scientists, engineers, and other experts in the seismic safety field need access to the site of an earthquake to study the actual damage caused by an earthquake. The studying of the response of buildings to the motion of an actual earthquake will aid the identification of design standards and other measures needed to minimize potential loss of life and property damage.

It is the intent of the Legislature to provide needed funding to allow scientists and other experts to inspect earthquake damage, wherever it may occur, and to collect data for uses in protecting life and property against the damaging effects of an earthquake in California.

SEC. 2. Section 8690.4 of the Government Code is amended to read:

8690.4. The Controller shall establish the following five special accounts in the Natural Disaster Assistance Fund:

(a) The Public Facilities Account, into which shall be paid all resources of the appropriation made by Section 4 of Chapter 624 of the Statutes of 1973, any money hereafter appropriated by the Legislature for allocation for public facilities projects, and any income from investment of moneys in the account and payments by local agencies in reimbursement of moneys disbursed from the account, including deferred payments with charges, pursuant to Section 8686.8.

(b) The Street and Highway Account, into which shall be paid all resources transferred from the Street and Highway Disaster Fund, any money received from the federal government as reimbursement to any city or county for expenditures from funds allocated, transferred or expended pursuant to this chapter for a street and highway project, any money hereafter appropriated by the Legislature for allocation for street and highway projects, and any income from investment of moneys in the account and payments by local agencies in reimbursement of moneys disbursed from the account including deferred payments with charges, pursuant to Section 8686.8.

(c) The 1983 Natural Disasters Account, into which shall be paid all moneys appropriated by the Legislature for allocation to those who have incurred losses or expenses resulting from the Coalinga earthquake of May 2, 1983, or the Morgan Hill earthquake of April 24, 1984, as follows:

(1) To reimburse local agencies for personnel overtime costs and for supplies used for disaster assistance.

(2) To provide for the repair, cleanup, and reconstruction of damaged public facilities.

(3) To provide state matching funds for federal assistance.

(4) To provide other assistance as the Director of the Office of

Emergency Services deems necessary to carry out the provisions of this subdivision.

(d) The 1986 Flood Disaster Account, to be established by the Controller, into which shall be paid all moneys appropriated by the Legislature for allocation to reclamation and levee maintenance districts maintaining nonproject levees damaged by the storms and floods of February 1986.

(e) The Earthquake Emergency Investigations Account, into which shall be paid all moneys appropriated by the Legislature to the Seismic Safety Commission for allocation for the purpose of enabling immediate investigation of damaging earthquakes. Allocations may be made by the commission to assist organizations which have incurred expenses in the course of conducting earthquake investigations. Allocations may be made to cover the following expenses:

(1) Travel, meals, and lodging.

(2) Publishing of findings.

(3) Contractor assistance in the investigation.

(4) Other expenses which the commission may allow as necessary to assist the investigation.

SEC. 3. Section 2211 is added to the Public Resources Code, to read:

2211. The department is the primary state agency responsible for geologic hazard review and investigation. In that capacity, the department is responsible for the seismological, geological, and strong motion aspects of earthquake investigations.

SEC. 4. Section 2804.6 is added to the Public Resources Code, to read:

2804.6. (a) The department, in consultation with the Seismic Safety Commission, shall prepare a feasibility study evaluating the effectiveness of an early warning system to detect seismic activity along the San Andreas Fault north of the Los Angeles metropolitan area. The feasibility study shall include, but is not limited to, a study of all of the following:

(1) Possible scenarios for the probability, strength, direction, and location of seismic activity occurring along the San Andreas Fault north of the Los Angeles metropolitan area.

(2) Development, use, and transmission of a warning signal to announce significant seismic activity detected by the early warning system, including an analysis of the estimated lead time provided by the system.

(3) Technical and economic feasibility of implementing the early warning system. Possible applications include automated shutdown of pipelines, transportation systems, computer systems, and other vital lifelines which would be damaged in an earthquake.

(4) Assessment of the value of warnings to various elements of society, including public officials, schools, hospitals, police, fire stations, private industry, critical defense contractors, and gas, oil,

and electrical industries. The assessment should include an estimate of the value of a warning as a function of the warning time and its reliability.

(5) Description of the funding, management, reliability, and liability aspects of the system.

(b) The department shall submit the feasibility study to the Governor's Office and to the Legislature by July 1, 1988.

SEC. 5. (a) The sum of one hundred thousand dollars ($100,000) is hereby transferred from the General Fund to the Earthquake Emergency Investigations Account in the Natural Disaster Assistance Fund and is hereby appropriated to the Seismic Safety Commission for allocation pursuant to subdivision (e) of Section 8690.4 of the Government Code.

(b) Notwithstanding any other provision of law, the sum of two hundred thousand dollars ($200,000) is hereby appropriated from the Insurance Fund to the Department of Conservation for the purposes of carrying out the feasibility study specified in Section 2804.6 of the Public Resources Code.

O

# APPENDIX B

## OBSERVATIONS OF JAPANESE SYSTEMS

# Appendix B

# Observations of Japanese Systems

## Introduction

During June 1988, two EWS project members visited Tokyo, hosted by Japan Railways, to study the variety of earthquake-related response systems supported by the Japanese government and by private industry there. In general, the systems observed were "alerting" systems, rather than warning systems, in that response at a site occurs after the shaking begins. We define a warning system here as one that attempts to enable mitigating action prior to the onset of strong shaking (but after the earthquake initiates). In Japan, the only example of a true warning system is the new system being installed and tested by Japan Railways for the Bullet Train.

## Japan Railways

The most well known of earthquake "warning" systems is that operated by the privately-owned and operated Japan Railways (JR) for its *shinkansen* ("bullet train"). The system that has been in operation for over 20 years contains a number of seismic sensors distributed along JR's tracks. When ground motion exceeds a specified value, power to a particular section of track is cut, stopping or slowing the bullet trains within or entering that section. This system could be considered an alerting or post-shaking response system since a train travelling over a section of track that is being damaged receives no warning. Nevertheless, the system does provide "warning" to trains that are entering a section of track that may have incurred earthquake damage.

This system has been in operation since 1966. During its first 20 years of operation, it stopped the train 100 times (averaging five times per year). Only twice were the tracks bent, but not enough to damage the train. These alarms were, however, caused by earthquakes properly triggering the system. They should not, therefore, be considered system failures. In 1987, engineers retuned the triggering algorithm, reducing the number of earthquake alarms from five to two per year. In addition, JR has experienced less than about one false alarm per year resulting from electronic or sensor failure (based on five such alarms between 1980 and 1986).

The Japan Railways' Railway Technical Research Institute is developing a new system (called UrEDAS) based on distributed seismic sensors (away from the tracks) that could provide true warning before the beginning of strong shaking. More sophisticated data analysis, rapidly estimating location and magnitude of the earthquake, should reduce the number of earthquake-generated false alarms (proper triggering of the system by an earthquake, but no track damage). This system is in the experimental and testing stages, to be installed in 1989. A more complete discussion of the JR systems can be found in Bito and Nakamura (1986) and in Nakamura and Tucker (1988).

Depending on the types of sensors and data processing included in a California EWS, one could expect similar rates of false alarms. Since the seismicity of California is about one-tenth that of Japan, a simple level trigger should produce one false alarm every five years (i.e., one-tenth of JR's two per year). The JR false alarms caused by instrument failures, about one every year, could be expected of a California system. The instrument failure false alarms could be reduced considerably if nearly simultaneous triggers of two instruments were required before an alarm. Thus, the false alarm rate for a California system could theoretically range from 0.2 to approximately 1.0 per year.

### Tokyo Gas

This private gas utility operates a network of 31 seismic stations distributed throughout the Tokyo metropolitan area. The Tokyo Gas service area is divided into nine zones, each containing at least three seismic stations. When shaking at two or more of the stations within a zone exceeds a specified level, that zone is isolated from the rest of the gas distribution system by an operator at the Tokyo Gas control center. The zone can be reintegrated into the overall system if a visual inspection of the lines shows no damage.

All the underground shopping malls and high-rise buildings of Tokyo have local seismic sensors. When shaking exceeds a specified level, gas to a facility is shut off by an operator at the Tokyo Gas control center. In addition, many homes in Tokyo have a system called "miconmeter," a gas meter equipped with a microcomputer. This meter will automatically shut off the gas supply to a house when flow is abnormally high or has continued for an abnormally long time, as well as in the case of an earthquake. Instructions are provided so that occupants may reset their own meter after notification via broadcast media. Tokyo Gas hopes that within a few years all homes in their service area will have this system.

All these earthquake alerting systems are designed to minimize the possibility of a post-earthquake fire caused by the gas system. Although the threat of fire has been lessened somewhat by the use of concrete and steel construction, the goal is to prevent the repeat of the conflagrations caused by historic earthquakes, such as the 1923 Kanto earthquake (M8.3) in Tokyo that killed 120,000 people. More than 440,000 homes were destroyed by that fire.

### Tokyo Subways

The Teito Rapid Transit Authority (TRTA) operates seven of the ten subway lines in Tokyo. To protect against the effects of earthquake damage to tracks and tunnels, TRTA operates an alerting system that contains three seismic sensors located on the outskirts of the metropolitan area. Ground motion from each of the three stations is telemetered to each of three subway control centers. Whenever peak acceleration exceeds a specified level, an operator at a control center radios train operators, instructing them to stop their subway train. After any local shaking has subsided, the train operator may proceed slowly to the nearest station, while looking for any damage to the subway tracks and tunnels.

## Other Japanese Alerting Systems

Two other earthquake alert systems that exist in Tokyo. All high-rise buildings have a system that causes the elevators to proceed to the nearest floor and stop if local shaking exceeds a specified level. This type of system is used throughout California. Also, loudspeakers are placed in schools and scattered throughout the cities surrounding Tokyo. The speakers announce that an earthquake has occurred. (The public warning systems in Nakano, Chiba and downtown Tokyo are automatically activated with tape-recorded messages.)

## Discussion of Japanese Systems

As stated above, with the exception of the Japan Railways system, all the Japanese systems observed are *alerting*, rather than *warning* systems. JR is currently developing a system that will improve its warning capabilities. Of importance to our review is the fact that, even though the JR earthquake warning system has been in operation for more than 20 years, the system is still limited to use along railroad lines. Japan Railways is interested in providing signals to other organizations, perhaps as a commercial enterprise. The success of this venture will no doubt depend on JR's success in providing reliable and timely warnings with the new UrEDAS.

# APPENDIX C

# MODIFIED MERCALLI INTENSITY SCALE

# OF WOOD AND NEUMANN

# Appendix C

## Modified Mercalli Intensity Scale of Wood and Neumann, and its Relation to the Rossi–Forel Scale

The numbers in parentheses in the left margin and the initials R.F. refer to the Rossi–Forel intensity scale.

**I** [I R.F.]

Not felt — or, except rarely under especially favorable circumstances.
Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced;
sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

**II** [I to II R.F.]

Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons.
Also, as in grade 1, but often more noticeably:
sometimes hanging objects may swing, especially when delicately suspended;
sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced.

**III** [III R.F.]

Felt indoors by several, motion usually rapid vibration.
Sometimes not recognized to be an earthquake at first.
Duration estimated in some cases.
Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
Hanging objects may swing slightly.
Movements may be appreciable on upper levels of tall structures.
Rocked standing motor cars slightly.

**IV** [IV to V R.F.]

Felt indoors by many, outdoors by few.
Awakened few, especially light sleepers.
Frightened no one, unless apprehensive from previous experience.
Vibration like that due to passing of heavy, or heavily loaded trucks.
Sensation like heavy body striking building, or falling of heavy objects inside.
Rattling of dishes, windows, doors; glassware and crockery clink and clash.
Creaking of walls, frame, especially in the upper range of this grade.
Hanging objects swung, in numerous instances.
Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

**V** [V to VI R.F.]

Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
Awakened many, or most.
Frightened few—slight excitement, a few ran outdoors.
Buildings trembled throughout.
Broke dishes, glassware, to some extent.
Cracked windows—in some cases, but not generally.
Overturned vases, small or unstable objects, in many instances, with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed, doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well–filled open containers.
Trees, bushes, shaken slightly.

**VI** [VI to VII R.F.]

Felt by all, indoors and outdoors.
Frightened many, excitement general, some alarm, many ran outdoors.
Awakened all.
Persons made to move unsteadily.
Trees, bushes, shaken slightly, moderately.
Liquid set in strong motion.
Small bells rang—church, chapel, school, etc.

Damage slight in poorly built buildings.
Fall of plaster in small amount.
Cracked plaster somewhat, especially fine cracks; chimneys in some instances.
Broke dishes, glassware, in considerable quantity, also some windows.
Fall of knick–knacks, books, pictures.
Overturned furniture in many instances.
Moved furnishings of moderately heavy kind.

VII [VIII – R.F.]

Frightened all—general alarm, all ran outdoors.
Some, or many, found it difficult to stand.
Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
Waves on ponds, lakes, and running water.
Water turbid from mud stirred up.
Incaving to some extent of sand or gravel stream banks.
Rang large church bells, etc.
Suspended objects made to quiver.

Damage negligible in buildings of good design and construction, slight to moderate in well–built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent, walls to some extent.
Fall of plaster in considerable to large amount, also some stucco.
Broke numerous windows, furniture to some extent.
Shook down loosened brickwork and tiles.
Broke weak chimneys at the roof–line (sometimes damaging roofs).
Fall of cornices from towers and high buildings.
Dislodged bricks and stones.
Overturned heavy furniture, with damage from breaking.
Damage considerable to concrete irrigation ditches.

VIII [VIII + to IX – R.F.]

Fright general—alarm approaches panic.
Disturbed persons driving motor cars.
Trees shaken strongly—branches, trunks, broken off, especially palm trees.
Ejected sand and mud in small amounts.
Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
Damage slight in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw off panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.

IX [IX + R.F.]

Panic general.
Cracked ground conspicuously.
Damage considerable in (masonry) structures built especially to withstand earthquakes:
threw out of plumb some wood–frame houses built especially to withstand earthquakes;
great in substantial (masonry) buildings, some collapse in large part;
or wholly shifted frame buildings off foundations, racked frames;
serious to reservoirs; underground pipes sometimes broken.

X [X R.F.]

Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.
Landslides considerable from river banks and steep coasts.
Shifted sand and mud horizontally on beaches and flat land.
Changed level of water in wells.
Threw water on banks of canals, lakes, rivers, etc.

Damage serious to dams, dikes, embankments.
Severe to well–built wooden structures and bridges, some destroyed.
Developed dangerous cracks in excellent brick walls.
Destroyed most masonry and frame structures, also their foundations.
Bent railroad rails slightly.
Tore apart, or crushed endwise, pipe lines buried in earth.
Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI Disturbances in ground many and widespread, varying with ground material.
Broad fissures, earth slumps, and land slips in soft, wet ground.
Ejected water in large amount charged with sand and mud.
Caused sea–waves ("tidal" waves) of significant magnitude.
Damage severe to wood–frame structures, especially near shock centers.
Great to dams, dikes, embankments, often for long distances.
Few, if any, (masonry) structures remained standing.
Destroyed large well–built bridges by the wrecking of supporting piers, or pillars.
Affected yielding wooden bridges less.
Bent railroad rails greatly, and thrust them endwise.
Put pipe lines buried in earth completely out of service.

XII Damage total—practically all works of construction damaged greatly or destroyed.
Disturbances in ground great and varied, numerous shearing cracks.
Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.
Wrenched loose, tore off, large rock masses.
Fault slips in firm rock, with notable horizontal and vertical offset displacements.
Water channels, surface and underground, disturbed and modified greatly.
Dammed lakes, produced waterfalls, deflected rivers, etc.
Waves seen on ground surfaces (actually seen, probably, in some cases).
Distorted lines of sight and level.
Threw objects upward into the air.

# APPENDIX D

# EARTHQUAKE WARNING SYSTEM

# SURVEY MATERIALS

STATE OF CALIFORNIA—THE RESOURCES AGENCY GEORGE DEUKMEJIAN,

DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY
DIVISION HEADQUARTERS
1416 NINTH STREET, ROOM 1341
SACRAMENTO, CA 95814
(Phone 916—445-1825)

«contact»
«title»
«company»
«address»
«city», «state» «zip»

«date», 1988

Dear «salute»:

I would like to take this opportunity to thank you for agreeing to participate in the Earthquake Early Warning System (EWS) study. As my staff discussed with you earlier this week, we are conducting, in cooperation with the California Seismic Safety Commission and under the authority of Chapter 1492, California Statutes of 1986, a study of the technical and economic feasibility of an EWS in California. The study is to include an assessment of the value of an EWS in southern California for various elements of society, "including public officials, schools, hospitals, police, fire stations, private industry, critical defense contractors, and gas, oil, and electrical industries."

In order to assess the potential costs and benefits of an EWS, as well as identify potential user requirements of an EWS, we are requesting the cooperation of organizations like yours to complete the enclosed *confidential* survey. The survey requests information in the following categories:

- specific facility data,
- earthquake risk,
- potential uses of an EWS in your facility, and
- consequences, estimated costs and benefits associated with an EWS.

To better describe an EWS and to provide you with information on the potential earthquake risk you may face, we have included an *Earthquake Early Warning System Survey* information packet along with various hypothetical seismic maps and a Technical Appendix. After you have had an opportunity to review these materials, Michael Reichle of my staff will contact you within a few days to answer any questions you may have. At that time, we will make arrangements to meet with you to pick up the completed survey and clarify your responses to our inquiry. In order to insure that the study is completed in accordance with the timeline specified by the Legislature, we ask that the survey be completed by the time we meet with you--approximately two weeks after you receive it.

We realize that completing the survey and working with our staff may be time consuming. Without accurate data, however, our conclusions will not be valuable. We believe that it is important to California to have an accurate assessment of the costs and benefits of an EWS. Such an assessment is possible only with your cooperation.

Finally, let me stress that your responses will be used for research purposes only and will be kept strictly *confidential*. If you have any questions, please feel free to call Michael Reichle at (916) 323-9976. Thank you again for your interest and cooperation.

Sincerely,

Brian E. Tucker
Acting State Geologist

Enclosures

## EARTHQUAKE EARLY WARNING SYSTEM SURVEY

California Department of Conservation
Division of Mines and Geology
October 1987

### ACKGROUND

Chapter 1492, California Statutes of 1986 (Senate Bill No. 1238, Roberti), requires at the Department of Conservation, Division of Mines and Geology, in cooperation with the ismic Safety Commission, conduct a feasibility study on an earthquake Early Warning System WS). The 1987 Budget Act (Chapter 135/87) subsequently included funding for this study ring the 1987-88 and 1988-89 fiscal years.

The scope of this study includes the technical and economic feasibility of an EWS for the n Andreas fault north of the Los Angeles metropolitan area. In addition, the Division is to sess the value of the warnings for various elements of society, "including public officials, hools, hospitals, police, fire stations, private industry, critical defense contractors, and gas, , and electrical industries."

The purpose of this survey is to poll selected potential EWS users to determine their erests, needs, and concerns regarding an EWS. In addition, the survey is to assist in the sessment of the potential costs and benefits of such a system.

### STORICAL SEISMICITY AND DAMAGE POTENTIAL IN SOUTHERN CALIFORNIA

In historical times, southern California has been rocked by numerous damaging rthquakes including the 1933 Long Beach and 1971 San Fernando earthquakes. The San rnando earthquake (M 6.4) was felt over an area of 80,000 square miles and resulted in over 000 casualties. The economic loss due to this moderate earthquake exceeded $500 million in 71 dollars. The most significant historical southern California earthquake in terms of mage *potential* is the great earthquake of January 1857. This event ruptured the San Andreas ult from the northern reaches of San Luis Obispo County to approximately 15 miles northwest San Bernardino. Historically, the approximately 220 miles of surface offset is second only to e great 1906 event that ruptured 270 miles of the San Andreas fault from Shelter Cove umboldt County) to San Juan Bautista, south of San Jose. The 1857 surface offset averaged out thirteen feet and its peak offset exceeded thirty feet. It was felt as far north as Marysville d Sacramento, as far east as Las Vegas, and as far south as Baja California. The duration of felt otion exceeded two minutes in both Sacramento and San Diego.

In 1981, the Federal Emergency Management Agency (FEMA) estimated that a repeat of e great 1857 earthquake in southern California today would cause between 15,000 and ,000 casualties, depending on the time of day. Property losses for a repeat of this event were timated to be approximately $20 billion in 1981 dollars. There is considerable uncertainty garding the probability of a repeat of the 1857 event over the next few decades. However, obability estimates generally exceed 50 percent for the occurrence of at least one event of agnitude 7.5 or greater on a portion of the southern San Andreas fault in the next 20 years. ease refer to Appendix A for a more detailed discussion on a repeat of the 1857 earthquake.

### ESCRIPTION OF AN EARLY WARNING SYSTEM

A seismic early warning system is an automated system that can both detect the currence of a potentially damaging earthquake and, under certain circumstances, provide a rning to specified California users from seconds up to two minutes prior to the onset of maging ground motion. The EWS is based on the fact that radio signals travel much faster than tentially damaging seismic waves (186,000 miles/second versus two miles/second).

Consequently, a radio transmission from the earthquake epicenter can "outrun" seismic waves to provide a short warning time if the user is sufficiently distant from the earthquake epicenter. For the case of a very large or great earthquake, where damaging motions occur at large distances from the epicenter, an EWS could provide many tens of seconds of warning time to those who are distant from the epicenter.

The EWS is *not* earthquake prediction, but depends on earthquake detection along densely instrumented faults, reliable communications and power, and real-time high-speed computer algorithms that estimate seismic source parameters, enabling the transmission of a ground motion warning. Because of the automated nature of an EWS, false alarms *can* occur. In addition, users could be affected by earthquakes occurring on unknown faults or faults not monitored by the EWS, or by an earthquake whose epicenter occurs too close to the user to provide a sufficient warning time.

The concept of an EWS is not new to earthquake engineering. In 1966, the Japanese National Railway installed for their "Bullet Train" a system that is triggered by a specified level of ground acceleration. The system, when triggered, automatically disengages the railway power grid, halting the trains, and thereby reducing the likelihood of derailment or collision.

## POTENTIAL USER APPLICATIONS OF EWS

A user facility could have automated systems to process EWS information. For example, the event alert or warning could trigger a pre-programmed sequence of responses such as the shut down of motion-sensitive equipment or the orderly evacuation of personnel from motion sensitive areas. Intelligent user systems could process the EWS information to evaluate whether the reported event exceeds a defined threshold and then to initiate other pre-programmed emergency responses.

Examples of possible uses or applications of an EWS signal include:

- *Manufacturers and utilities* could secure and/or stop the operation of potentially dangerous equipment.
- *Petroleum storage and refiners* could shut pipes/conduits carrying hazardous materials.
- *Electrical utilities* could shut off power in transmission lines subject to failure.
- *A gas utility* might save hours of inspection time with immediate knowledge of the ground surface rupture and inferences made on pipeline damage at fault and pipeline crossings.
- *Airports/military bases* could divert approaching aircraft and ground aircraft until runways are inspected.
- *Medical facilities* could switch to auxiliary power and surgical procedures could be halted.
- *Financial institutions* and other businesses dealing with vital records/transactions could switch to emergency power, or trigger an orderly shut-down of computer equipment.
- *Radio/TV stations* could broadcast a pre-recorded earthquake advisory.
- *Local government and the State Office of Emergency Services (OES)* could immediately implement the local/state emergency response plan for damaged areas, and allocate resources based on the EWS determined event epicenter, magnitude, distribution of fault rupture, and peak motion estimates along the fault.

Responses to an EWS signal could result in savings and/or avoided losses, including:

- avoided costs associated with repairing or replacing equipment that would have been damaged otherwise ,
- the value of production and/or sales that can be saved or resumed as a result of damage mitigation responses to an EWS signal,

- medical costs not incurred due to injuries avoided,
- loss of wages, and
- interest costs on equipment or inventory that would lie idle.

## :ARTHQUAKE EARLY WARNING SYSTEM SURVEY

Following the Technical Appendix, we have attached a series of questions. Your ioughtful consideration and answers to these questions will greatly assist us in evaluating the ieed for and interest in an EWS. These questions are grouped into three general subject areas: 1) Questions relating to your company and facilities, (2) Questions relating to earthquake isk, and (3) Questions relating to the applicability of an EWS to your facility's areas or perations. Although these questions may not appear to be directly relevant to your interest in ır need for an EWS, they are necessary to allow us to evaluate the use of an EWS in various ›usiness and facility configurations.

## TECHNICAL APPENDIX
## Discussion of An Earthquake Early Warning System

In 1982 the California Department of Conservation, Division of Mines and Geology, performed a lifeline earthquake planning scenario for a postulated event similar to the 1857 earthquake. Seismic intensity distribution maps, taken from that report, are shown in Figures 1A and 1B.

The predicted Rossi-Forel (RF) intensities are based on the postulated recurrence of a magnitude 8.3 earthquake on a segment of the San Andreas fault that ruptured in 1857. The projected intensities take into account the distance to the causative fault, and include the effects of near surface geology. The RF intensities used in the map have a scale range from less than 7 to 9, the larger number indicating a greater degree of intensity or damage. The RF intensities, however, do not necessarily apply to modern or high rise construction.

The intensities shown in Figure 1A and 1B are illustrative of both the geographic scale of the calamity, and the complexities involved in estimating ground shaking. It is problematic to evaluate seismic hazard and the risk to the various engineered structures and their contents without site specific information. *For these reasons the projected intensity or ground motion maps, such as those shown in Figures 1A through 4, are hypothetical and should only be used for comparing regional differences in seismic hazard.*

Figure 2 is a contour map of predicted peak ground acceleration in southern California given the occurrence of an 1857 type event. The regressions used to create this map are based on a statistical compilation of horizontal peak ground accelerations instrumentally recorded from earthquakes throughout the state. The map does not take into account details of earthquake source complexity or variance in geological structure. The contours represent levels of peak ground acceleration (percent of g). Specifically, Figure 2 indicates that there is a 20 percent probability of exceeding (20 percent probability of exceedance) the peak ground acceleration specified at each 10 percent of g contour interval. Levels of acceleration corresponding to 50 percent probability of exceedance would be about one half those in Figure 2. *We emphasize that earthquake induced damage is a complex function of acceleration level, duration, local ground condition, and construction type and quality. Figure 2 shows just one parameter for an 1857 type event. Durations of more than two minutes of strong ground shaking may be a more critical factor in structural response.*

Figure 3 is similar to Figure 2 except that the ground motion parameter is peak response velocity, calculated assuming a repeat of an 1857 type event, for a five percent damped oscillator with a one second period recording on a soil site. Figures 2 and 3 are perhaps most useful to structural engineers. We include them for completeness, especially for those potential users with in-house engineering expertise.

Figures 1 through 3 are simplified illustrations of the motions that could occur given the occurrence of a specified earthquake. Note that a number of faults, and/or regional areas, could be monitored by an EWS. It is illustrative to consider the probability of occurrence of potentially damaging earthquakes on both the southern San Andreas and the San Jacinto faults. A contour map of *probabilistic* peak ground acceleration is shown in Figure 4. The probability of exceedance of peak ground acceleration is 20 percent over the next 50 years. This map is similar to Figure 1 except that Figure 4 takes into account a model for the probability of occurrence of a number of earthquakes on the San Andreas and San Jacinto faults in the next 50 years. Note that this model does not incorporate other potentially damaging faults that are distributed throughout southern California. According to this model, the Los Angeles area would have an approximate 20 percent chance of exceeding a peak horizontal acceleration of 20 percent g in the next 50 years based on earthquake recurrence models *only* for the San Andreas and San Jacinto faults. *However, because there are other faults in southern California which may cause earthquakes, the probabilities represented in Figure 4 may understate the actual risk of damaging ground motion.*

## PRELIMINARY DESCRIPTION OF EWS COMPONENTS

Although it is premature to describe the system design in detail, it may be useful to describe the general system components. An EWS might consist of five basic components:

(1) a network of remote ground motion sensors with transmitters,

(2) a receiver/transmitter to collect and transmit data to a central processing facility,

(3) a central processing system to analyze data and make recommendations to remote users,

(4) a communications system to report the warning to the remote users, and

(5) an automated response to that warning by the user.

The EWS sensor network might consist of a relatively dense system of sensors in the proximity of major faults selected in southern California. These sensors could measure and report a variety of motions, including one or more of the following: time of exceedance of one or more specified levels of ground acceleration; continuous reporting of one or more orthogonal components of displacement, velocity, or acceleration; continuous or discrete amounts of fault surface rupture displacement.

Communication of the seismic data to the central processing facility and the subsequent early warning from the central processing facility to the remote user could be accomplished by telephone, microwave, radio, satellite, fiber-optics transmission media or some combination thereof.

Seismic data acquisition and data processing, while not necessarily the most expensive aspect of the system, is one of the most critical system components. It would be performed in real-time by one or more dedicated computers at a location remote from the network. Computer algorithms developed for event detection and seismic parameter estimation would be tested using small earthquakes that occur more frequently within the EWS network. In addition to seismic parameter estimation of events on the fault, the computer algorithms must also sort out the events that occur on the periphery of the system that may not be relevant to the EWS. The EWS user could test system response by participating in system drills.

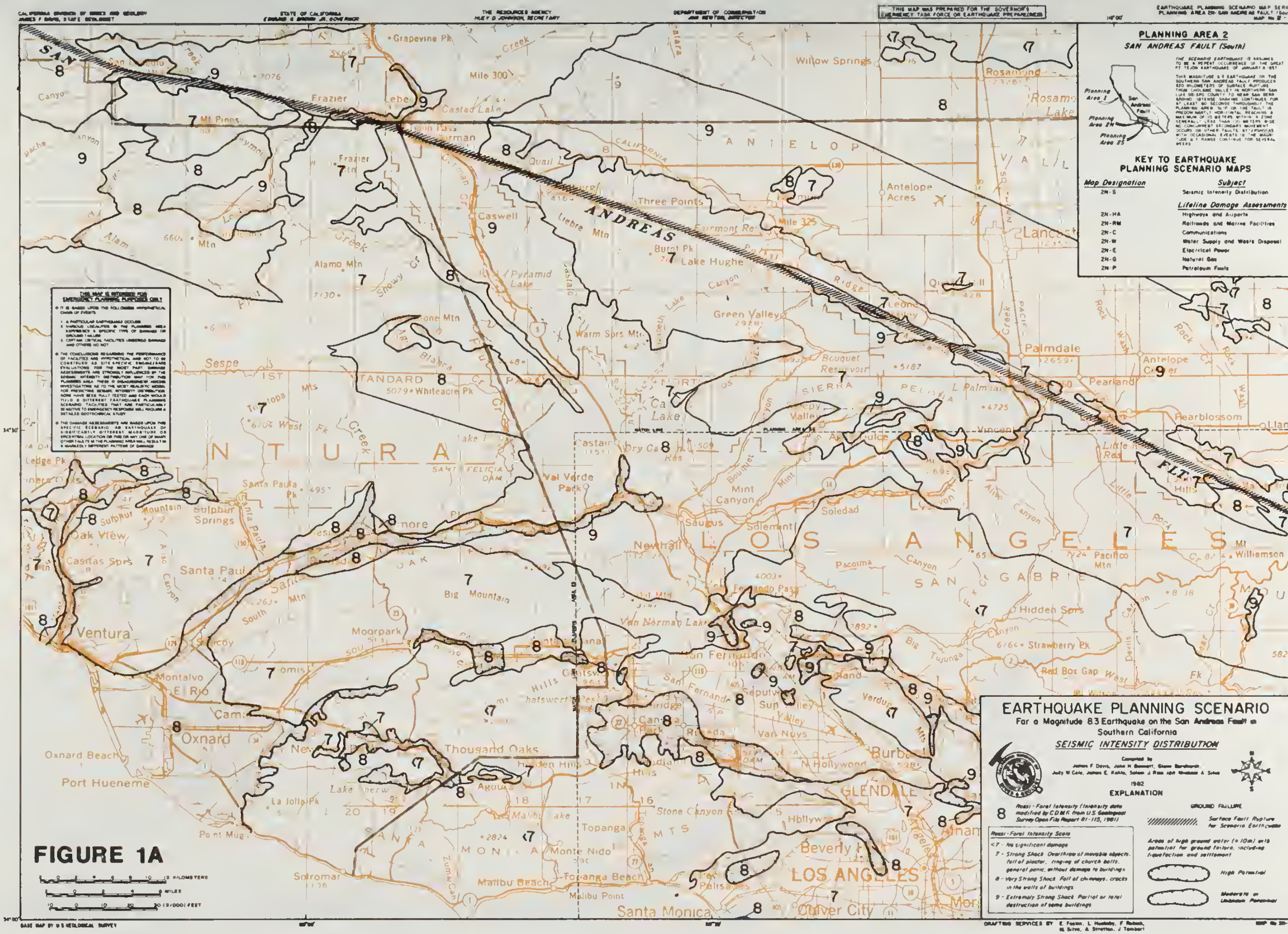
An approximate range of possible warning times are estimated in Figures 5 and 6. The minimum and maximum times represent the arrival times of the seismic S-wave (shear wave) from an 1857 type earthquake. If the EWS were in operation along this segment of the San Andreas fault, the contours in Figure 5 indicate the shortest possible warning times for earthquakes centered at the closest point along the fault. The maximum times, shown in Figure 6, assume that the earthquake epicenter is centered at the most distant portion of the fault. For example, a user located at Long Beach could experience from twenty to ninety seconds of warning time before the arrival of the initial seismic S-wave (for an even occurring along the segment of the San Andreas fault shown in Figures 5 and 6. *We note that these warning times do not reflect the time required by the EWS to detect and locate the event and transmit a signal to the user.* However, damaging motions may not occur until after the arrival of the initial S-wave. Thus, the estimated warning times of the EWS may still provide potential users with useful warning.

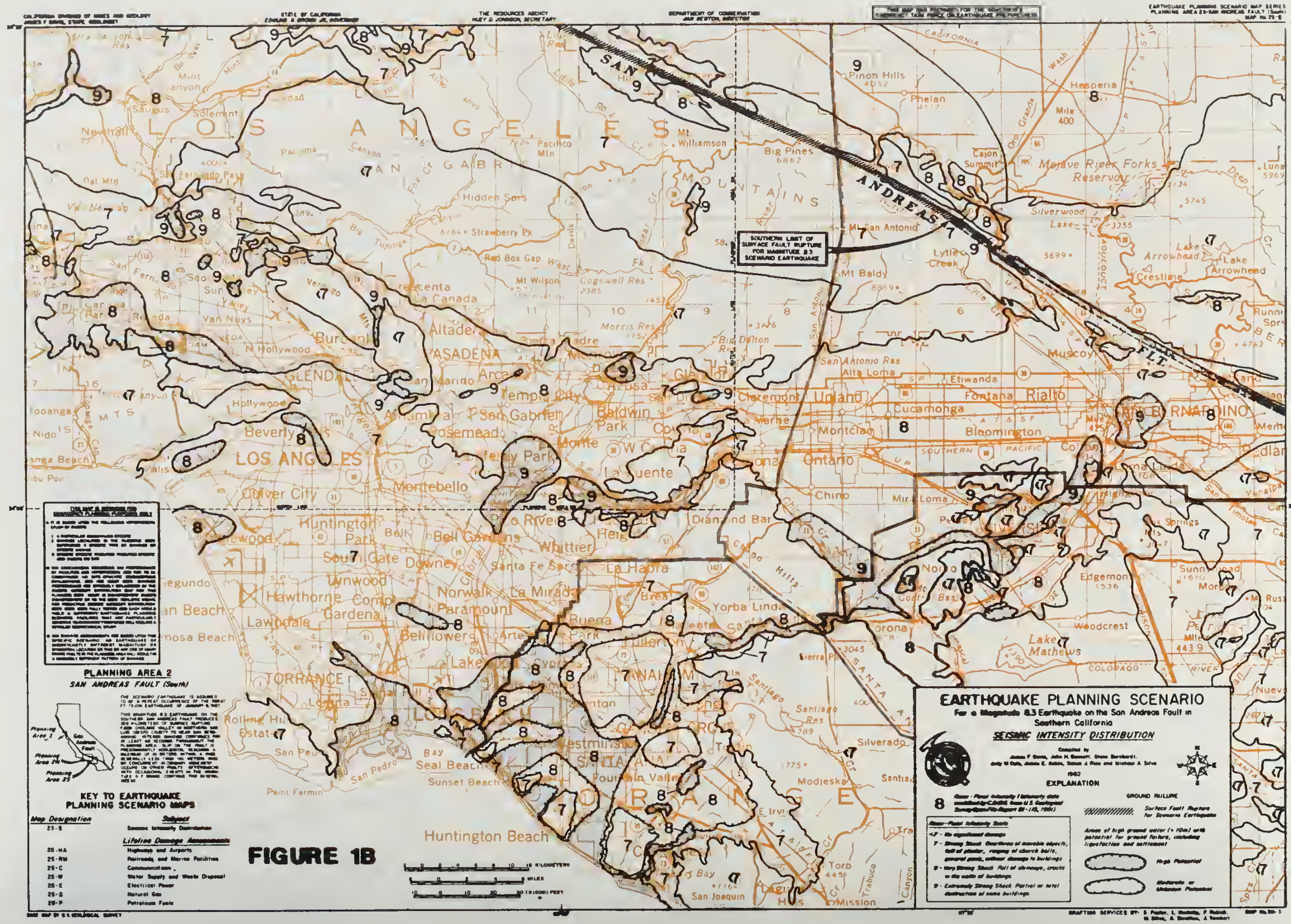
## POSSIBLE INFORMATION FROM THE EWS TO USERS

The information that could be gathered, interpreted, and transmitted to users of the EWS is dependent on the system capabilities, the characteristics of the specific earthquake that may occur, the users geographic location with respect to the earthquake's epicenter, and the ground motion sensitivity of the users' structure(s), systems, contents, and operations. Depending on these parameters, the system warning could consist of a (1) simple alert signal indicating that a possibly damaging event is occurring, (2) multiple level signal giving an alert and some range of magnitude or damage probability, or, alternatively, (3) warning signal and earthquake source information which the user could use to estimate ground motion and damage probabilities.

More specifically, users might benefit from one or more of the following:

- notification of the occurrence of a significant earthquake in southern California possibly prior to the onset of strong ground motion (warning time dependent on user proximity to the earthquake epicenter),
- notification of an event on the monitored fault(s),
- estimated epicentral location,
- estimated P- and S-wave onset times for each user,
- predicted onset time of strong ground motion,
- current event magnitude estimate with updates,
- predicted peak ground motions, possibly including adjustments for users with site-specific corrections,
- transmission of special codes to each user that would electronically enable or initiate a user's automated system based on pre-defined criteria,
- estimates of the spatial extent and amount of surface fault rupture,
- reliability estimates of the information issued to the user, and
- rapid post-event magnitude estimates, in addition to the probable extent of surface rupture and estimates of the location of high damage areas.


EARTHQUAKE PLANNING SCENARIO
For a Magnitude 8.3 Earthquake on the San Andreas Fault in Southern California
SEISMIC INTENSITY DISTRIBUTION
1982
EXPLANATION
PLANNING AREA 2
SAN ANDREAS FAULT (South)
KEY TO EARTHQUAKE PLANNING SCENARIO MAPS
Map Designation
Subject
Seismic Intensity Distribution
Lifeline Damage Assessments
Highways and Airports
Railroads and Marine Facilities
Communications
Water Supply and Waste Disposal
Electrical Power
Natural Gas
Petroleum Fuels
GROUND FAILURE
Surface Fault Rupture for Scenario Earthquake
High Potential
Moderate or Unknown Potential
SAN ANDREAS
LOS ANGELES
VENTURA
Palmdale
Lancaster
Ventura
Oxnard
Port Hueneme
Santa Monica
Culver City
Beverly Hills
Glendale
Van Nuys
Thousand Oaks
Santa Paula
Newhall
Saugus
Frazier
Gorman
Pearblossom
Antelope Acres
Willow Springs
Rosamond
BASE MAP BY U.S. GEOLOGICAL SURVEY
FIGURE 1A


EARTHQUAKE PLANNING SCENARIO
For a Magnitude 8.3 Earthquake on the San Andreas Fault in Southern California
SEISMIC INTENSITY DISTRIBUTION
1982
EXPLANATION
GROUND FAILURE
Surface Fault Rupture for Scenario Earthquake
Areas of high ground water (< 10m) with potential for ground failure, including liquefaction and settlement
High Potential
Moderate or Unknown Potential
SOUTHERN LIMIT OF SURFACE FAULT RUPTURE FOR MAGNITUDE 8.3 SCENARIO EARTHQUAKE
PLANNING AREA 2
SAN ANDREAS FAULT (South)
KEY TO EARTHQUAKE PLANNING SCENARIO MAPS
Map Designation
Subject
Seismic Intensity Distribution
Lifeline Damage Assessments
Highways and Airports
Railroads and Marine Facilities
Communications
Water Supply and Waste Disposal
Electrical Power
Natural Gas
Petroleum Fuels
SAN ANDREAS FLT.
LOS ANGELES
SAN GABRIEL MOUNTAINS
ORANGE
PASADENA
LOS ANGELES
SAN BERNARDINO
Huntington Beach
Long Beach
Torrance
Santa Ana
Anaheim
Ontario
Pomona
Riverside
Whittier
Glendale
Beverly Hills
Culver City
Upland
Fontana
Rialto
Cucamonga
Hesperia
Phelan
Pinon Hills
Mt San Antonio
Mt Baldy
Big Pines
Lake Arrowhead
Silverwood Lake
Chino
Corona
Norco
Lake Mathews
Newhall
Van Nuys
Burbank
Alhambra
Downey
Norwalk
Compton
Hawthorne
Lawndale
Bellflower
Paramount
Fullerton
Yorba Linda
Brea
La Habra
Westminster
Fountain Valley
Seal Beach
Sunset Beach
San Pedro
Point Fermin
Modjeska
Silverado
San Joaquin
Mission
FIGURE 1B

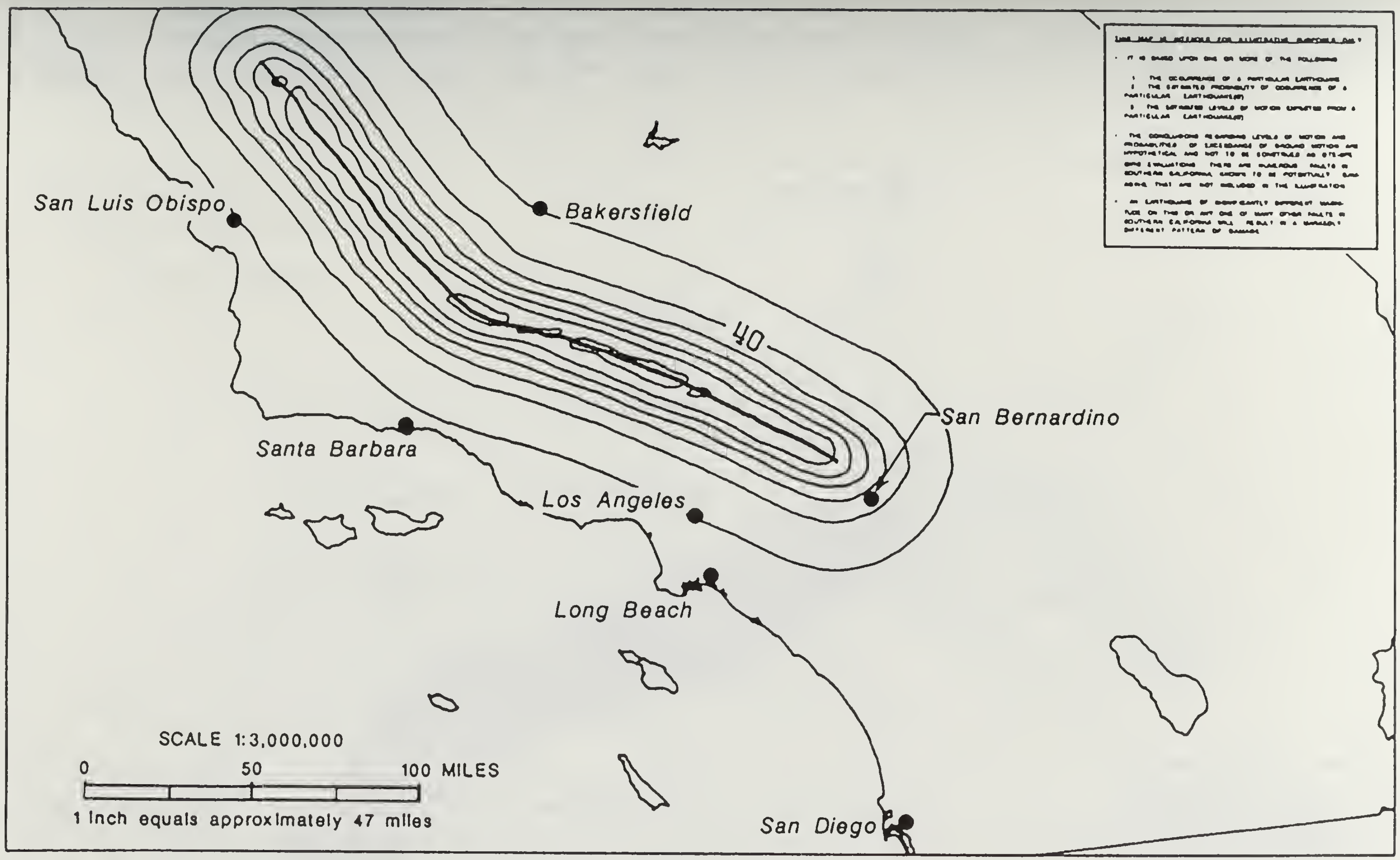



**Figure 2.** Predicted peak horizontal ground acceleration at the 20 percent exceedance level for an earthquake occurring on the 1857 ruptured segment of the San Andreas fault. Contour intervals represent 20 percent of g.

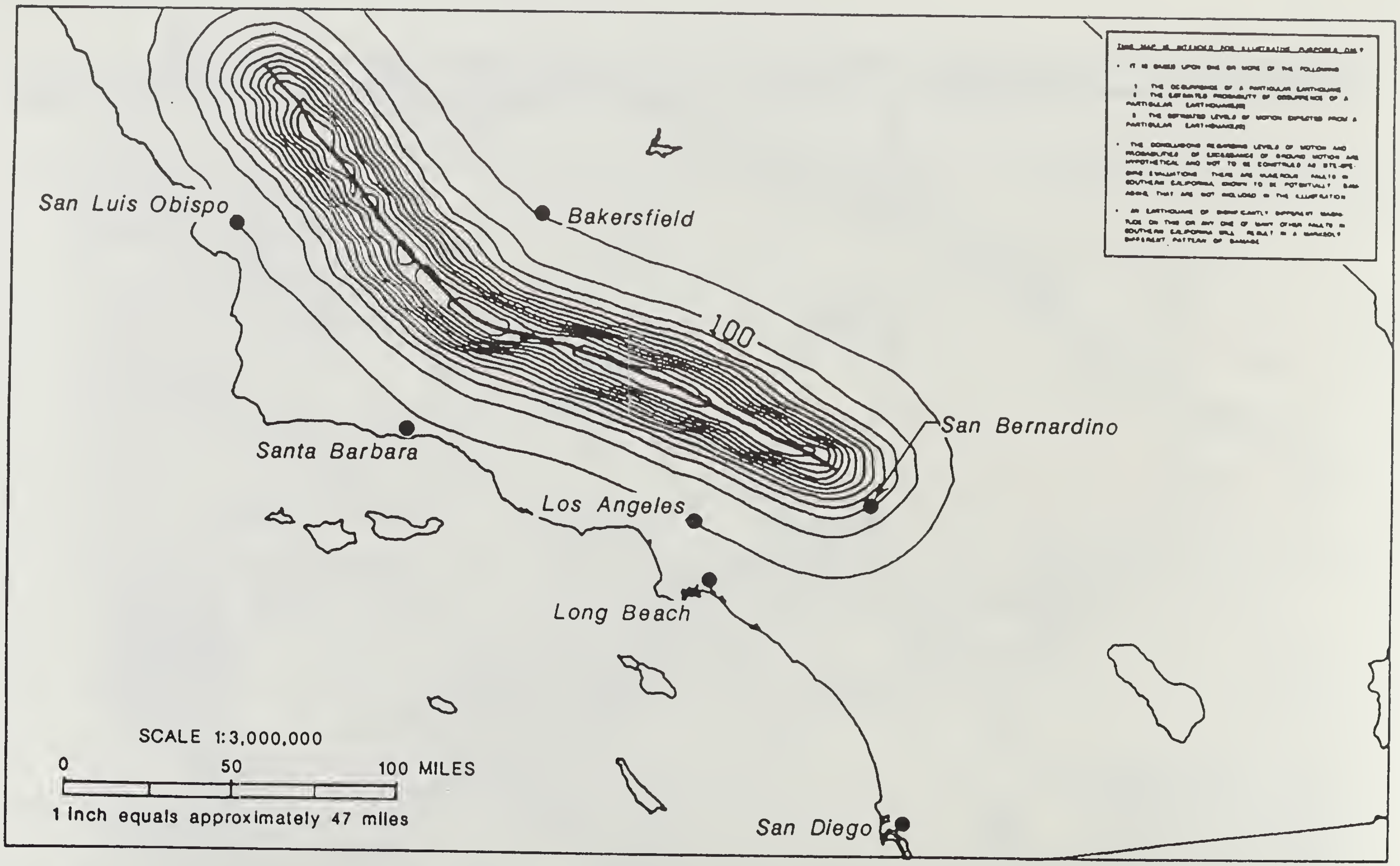



**Figure 3.** Predicted pseudo-velocity response, at the 20 percent exceedance level, for a 5 percent damped one second period oscillator on soil sites. Earthquake same as Figure 2. Contour intervals represent 50 centimeters per second.

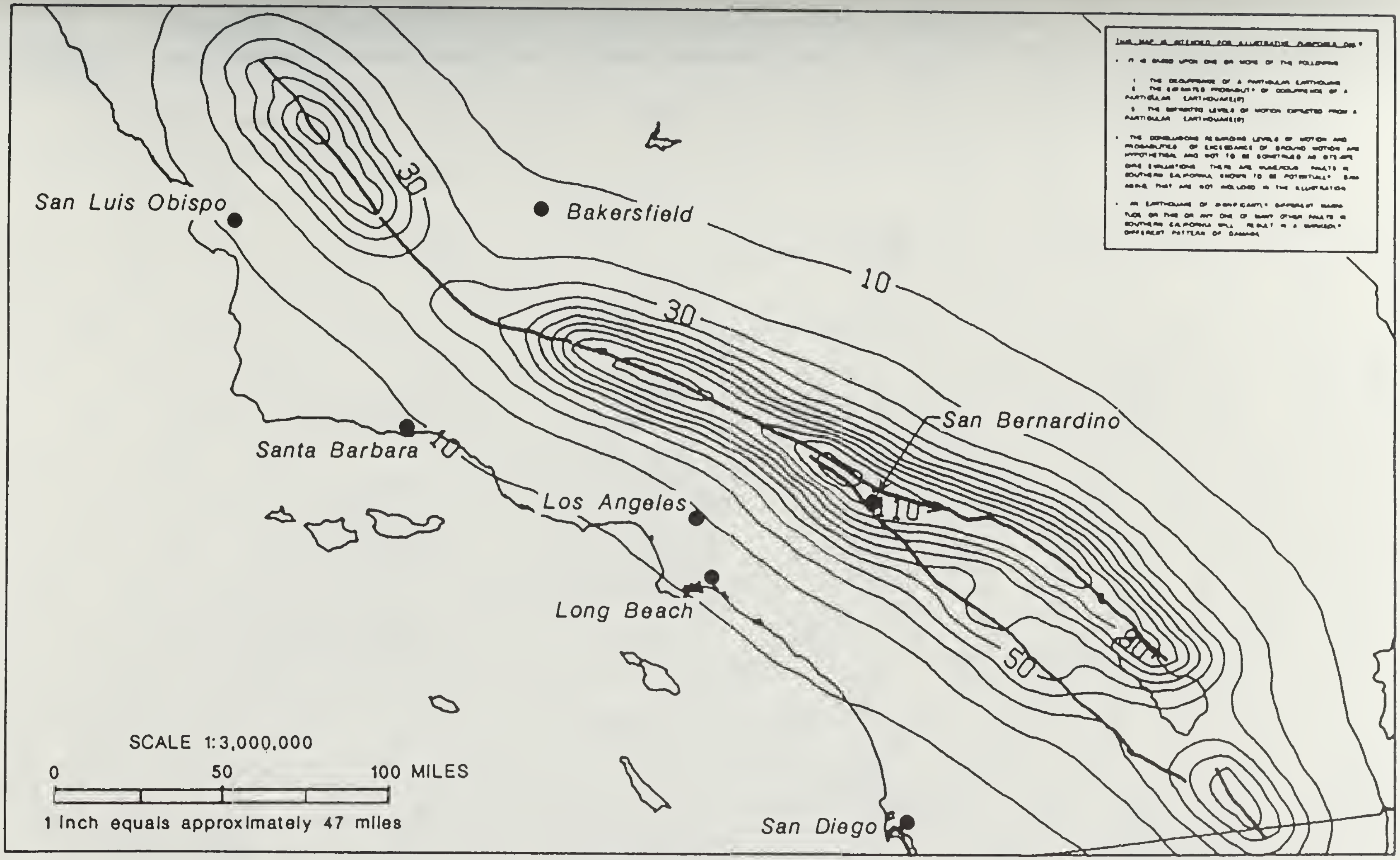



**Figure 4.** Probabilistic peak ground acceleration for earthquakes occurring on the southern San Andreas and San Jacinto faults. The probabilistic acceleration is computed at the 20 percent exceedance level for a period of the next fifty years. Contour intervals represent 10 percent of g.

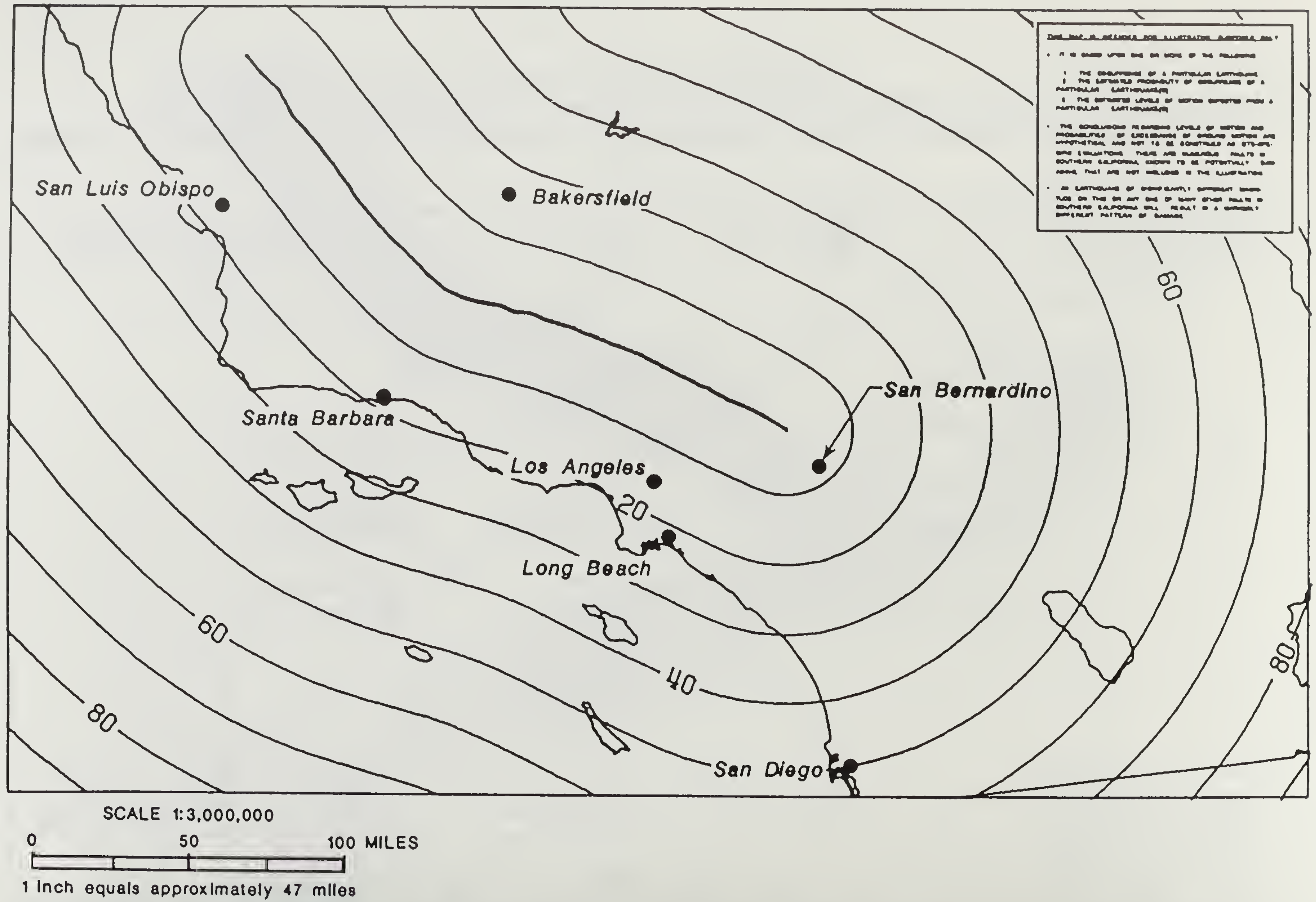



**Figure 5.** Minimum shear wave travel time at locations distant from an 1857-type rupture. The times assume that the earthquake epicenter initiates at a point on the fault closest to the observer.

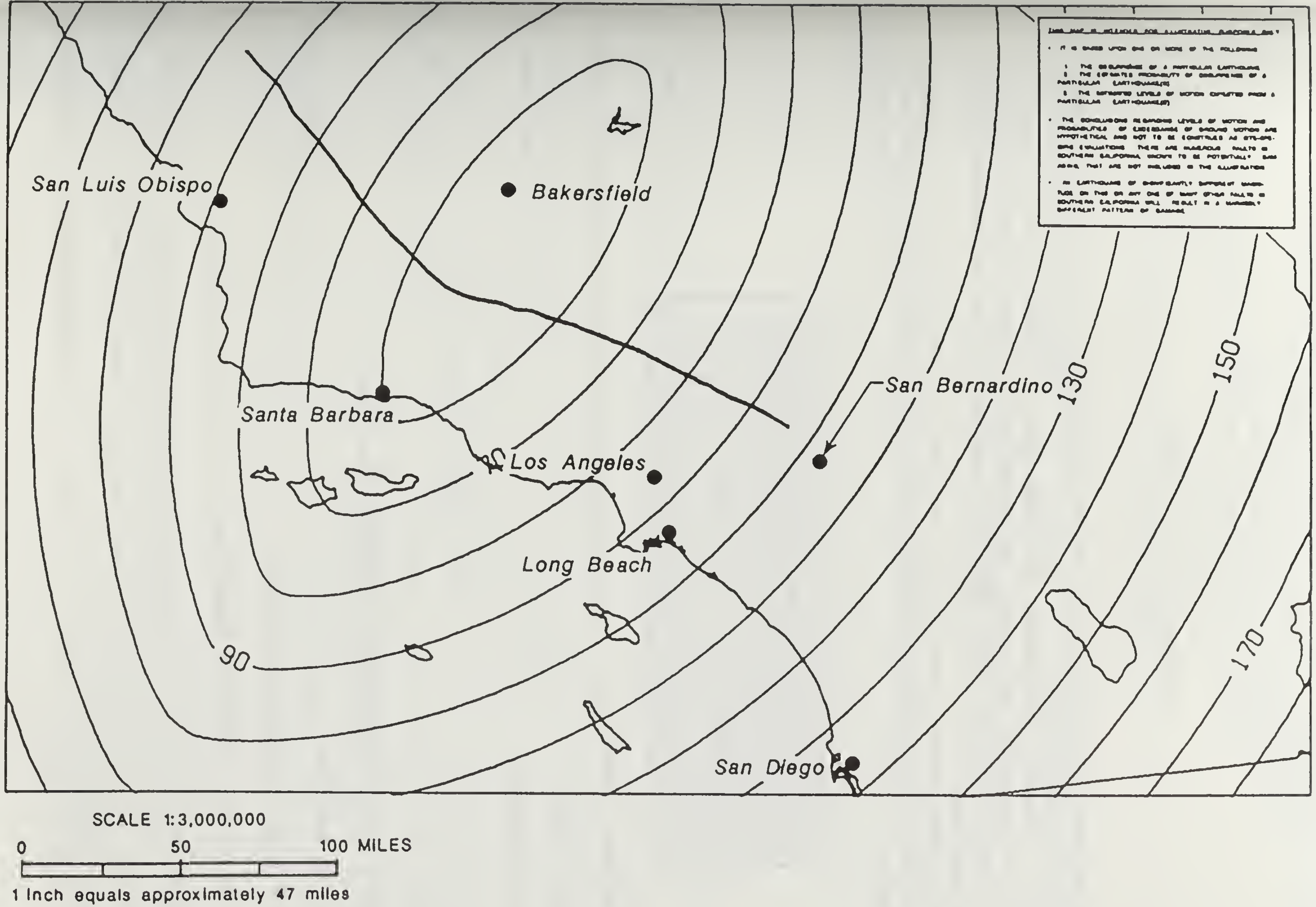



**Figure 6.** Maximum shear wave travel times at locations distant from an 1857-type rupture. The times assume that the earthquake epicenter initiates at a point on the fault farthest from the observer.

# EARTHQUAKE EARLY WARNING SYSTEM SURVEY

CALIFORNIA DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY
Early Warning System Project
630 Bercut Drive
Sacramento, CA 95814
(916) 323-9975

*The responses to this survey are for research purposes only and are to be kept strictly* ***confidential*** *by the State Geologist.*

*Please complete* ***one survey for each type of facility*** *utilized by your organization. In completing the survey, please select an* ***average or typical facility which best represents each facility type*** *that is operated by your organization within the specified study area .*

*The study area includes Fresno, Imperial, Kern, Kings, Los Angeles, Monterey, Orange, Riverside, San Benito, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Tulare, and Ventura Counties.*

---

**DO NOT COMPLETE BOX--FOR DMG USE ONLY**

USER ID__________ C. FAC: Y N

SURV. DATE_________ INT. DATE___________

LOC.____________________

Organization Name ________________________________________

Facility Name ________________________________________

Street Address ________________________________________

City __________________________ Zip Code ___________________

County __________________________

Standard Industrial Classification (SIC) Code (four digit) ___________

Type of Business ________________________________________

Total Number of Facilities in County _________________________

Total Number of Facilities in Study Area _______________________

Contact Person ________________________________________

Title ________________________________________

Contact Phone ________________________________________ acility Data

. How important is the threat of a major earthquake to operations in your facility?

__ extremely important
__ very important
__ important
__ slightly important
__ not important at all

. A. Do you carry earthquake insurance? YES_____

NO_____

B. Why or why not?

C. What is the total dollar value of coverage for your facility? $__________

D. What is the total dollar cost of the annual premiums? $__________

E. What is the percent deductible? _____percent

A. Do you carry fire insurance? YES_____

NO_____

B. Why or why not?

C. What is the total dollar value of coverage for your facility? $__________

D. What is the total dollar cost of the annual premiums? $__________

E. What is the percent deductible? _____percent

4. A. When was your facility constructed? 19___

B. What is the current design lifetime of your facility? ___________ years

5. What is the replacement value of your facility in 1987 dollars? $__________

6. What is the assessed property value of your facility in 1987 dollars? $__________

7. A. What is the total gross square footage of your facility at this location? __________gsf

B. How many stories does your facility include? __________stories

8. What is the construction type of your facility? *Please refer to the facility classes listed in Table 1 located at the end of this survey to answer this question.*

**Earthquake Risk**

9. A. Has your facility been seismically reinforced? YES_____

NO_____

If so, in what specific areas of the facility? When?

| B. Area Reinforced | C. When Reinforced |
|---|---|
| ____________________ | ____________ |
| ____________________ | ____________ |
| ____________________ | ____________ |
| ____________________ | ____________ |

). A. Are there "design earthquakes" for your facility? YES_____

NO_____

If so, what is the event magnitude, distance, and applicable fault?

| B. Magnitude | C. Distance | D. Applicable Fault |
|---|---|---|
| _________ | _______km | __________________ |
| _________ | _______km | __________________ |
| _________ | _______km | __________________ |

. If known for your facility, what are the predominant natural frequencies of structures at e facility?

| A. Structures | B. Natural Frequencies |
|---|---|
| ________________________________ | ________________ |
| ________________________________ | ________________ |
| ________________________________ | ________________ |

. If known, what are the engineering design motions for the structures described in Question ?

| A. Structures | B. Design Motions |
|---|---|
| ________________________________ | ______________ |
| ________________________________ | ______________ |
| ________________________________ | ______________ |

**Potential Uses, Consequences, Costs and Benefits of an EWS**

13. What areas, operations, or systems in, or resulting from, your facility are susceptible to strong ground motion or other hazards generated as a result of seismic activity? *Please list each area, operation, or system.* If known, what are the natural frequencies and/or design motions for these systems or system components?

| A. Area/Operation/System | B. Natural Frequency/Design Motion |
|---|---|
| ____________________ | ____________________ |
| ____________________ | ____________________ |
| ____________________ | ____________________ |
| ____________________ | ____________________ |

14. Which of the areas, operations, or systems in your facility identified in Question 13 could be secured, evacuated, shut down or disengaged so as to reduce the resultant earthquake damages or hazards if you received a few seconds to two minutes of warning prior to the onset of strong ground motion? How much warning time is required for each area, operation, or system? *For example, consider personnel safety, off-site safety (if internal parameters could potentially affect off-site, such as fire, flood, radioactive release), savings to equipment (could include computer disk drives, high speed rotational machinery such as turbines), improved response to disaster mitigation (setting into motion employee response plans).*

| A. Area/Operation/System | B. Required Warning Time (secs) |
|---|---|
| ____________________ | ____________________ |
| ____________________ | ____________________ |
| ____________________ | ____________________ |
| ____________________ | ____________________ |

15. What would be the estimated savings or avoided losses in dollars associated with *each* area, operation, or system in Question 14 if they could be secured, evacuated, shut down or disengaged prior to strong ground motion? (*For examples of potential savings or avoided losses, please refer to the Earthquake Early Warning System information packet, pages 2-3.)*

| A. Area/Operation/System | B. Estimated Savings/Avoided Losses |
|---|---|
| ____________________ | $____________________ |
| ____________________ | $____________________ |
| ____________________ | $____________________ |
| ____________________ | $____________________ |

6. If you subscribed to an EWS network, what would the signal be used for? *(Please check the nticipated uses of the signal and rank each checked response in order of importance on the right and side--1 for greatest importance, 6 for least importance, etc.)*

| | Uses | Ranking |
|---|---|---|
| ___ | automated response to mitigate damage | ______ |
| ___ | human response to mitigate damage | ______ |
| ___ | post-event description of strong motion | ______ |
| ___ | emergency response within your facility | ______ |
| ___ | operations contingencies | ______ |
| ___ | information purposes, not for response | ______ |

7. If you became a subscriber to an EWS, what would be the consequences and estimated costs your facility/operations if no earthquake occurs but the EWS transmits a warning? *Please pecify the consequences and the type and amount of costs incurred for each area, operation, or ystem identified in Question 14.*

| Area/Operation/System | Consequences | Estimated Costs ($) |
|---|---|---|
| __________________ | _________________________ | ______________ |
| __________________ | _________________________ | ______________ |
| __________________ | _________________________ | ______________ |
| __________________ | _________________________ | ______________ |

8. If the EWS were offered as a subscriber service, what would be the maximum monthly ollar amount you would be prepared to pay to receive a warning signal for each area, operation, r system as identified in Question 14 assuming that the system is 100 percent reliable? What rice would you pay if the system was 50 percent reliable (you receive a warning for only 50 ercent of the damaging earthquakes)?

| A. Area/Operation/System | B. Monthly Amount if 100 Percent Reliable | C. Monthly Amount if 50 Percent Reliable |
|---|---|---|
| ___________________________ | $_______________ | $_____________ |
| ___________________________ | $_______________ | $_____________ |
| ___________________________ | $_______________ | $_____________ |
| ___________________________ | $_______________ | $_____________ |

19. Are there any other facilities owned/operated by your organization that are not within the study area but which could use an EWS? Please list.

20. Are you aware of other agencies, companies, or individuals who may be interested in the EWS?

21. Do you have any general comments or suggestions about the EWS or its purpose?

22. In your words, what would be the benefit of an EWS if it were implemented in California?

We greatly appreciate your participation in this survey. You will be forwarded a copy of the EWS study when it is completed.

## TABLE 1
## CONSTRUCTION TYPES
### Facility Classes and Descriptions

| lass | Description |
|---|---|
| | Wood Frame Buildings. *Does not include structures which are classified as wood frame for fire purposes but have concrete supported floors and/or some walls of unit masonry or concrete.* |
| C | Non-habitation--wood frame and frame stucco buildings, except (1) buildings which are over three stories in height, and (2) buildings which are over 3,000 square feet in ground floor area. |
| D | Wood frame and frame stucco buildings not qualifying under Class 1C above. |
| | **All-metal buildings** |
| A | All-metal buildings which are one-story in height and 20,000 square feet or less in ground floor area. Wood or cement-asbestos are acceptable alternatives to metal roofing and/or siding. |
| B | Buildings which would qualify as Class 2A except for exceeding area or height limitations. |
| | **Steel Frame buildings** |
| A | Buildings with a complete steel frame carrying all loads. Floors and roofs must be of poured-in-place reinforced concrete or of concrete fill on metal decking welded to the steel frame (open web steel joists excluded). Exterior walls must be non-load bearing and of poured-in-place reinforced concrete or of reinforced unit masonry. Buildings having column-free areas greater than 2,500 square feet (such as auditoriums, theaters, public halls, etc.) do not qualify. |
| B | Buildings with a complete steel frame carrying all loads. Floors and roofs must be of poured-in-place reinforced concrete metal, or any combination thereof, except that roofs on buildings over three stories may be of any material. Exterior and interior walls may be of any non-load bearing material. |
| C | Buildings having a complete steel frame with floors and roofs of any material (such as wood joist on steel beams) and with walls of any non-load bearing materials. |

Table 1 Continued

| Class | Description |
|---|---|
| | **Reinforced Concrete Buildings** |
| | **Combined Reinforced Concrete and Structural Steel Buildings** |
| | *Note: Class 4A and 4B buildings must have all vertical loads carried by a structural system consisting of one or a combination of the following: (a) poured-in-place reinforced concrete frame, (b) poured-in-place reinforced concrete bearing walls, (c) partial structural steel frame with (a) or (b). Floors and roofs must be reinforced concrete, except that materials other than reinforced concrete may be used for the roofs of buildings over three stories.* |
| 4A | Buildings with a structural system as defined by the note above with poured-in-place reinforced concrete exterior walls or reinforced unit masonry exterior walls. Not qualifying are buildings have column-free areas greater than 2,500 square feet (such as auditoriums, theaters, public halls, etc.) |
| 4B | Buildings having a structural system as defined by the note above with exterior and interior non-bearing walls of any material. |
| 4C | Buildings having (1) partial or complete load carrying system of precast concrete, and/or (2) reinforced concrete lift-slab floors and/or roofs, and (3) otherwise qualifying as Class 4A and 4B. |
| 4D | Buildings having a reinforced concrete frame, or combined reinforced concrete and structural steel frame. Floors and roofs may be of any material (such as wood joist on reinforced concrete beams) while walls may be of any non-load bearing material. |
| | **Mixed Construction** |
| 5A | Buildings having load bearing exterior walls of (1) poured-in-place reinforced concrete, and/or (2) precast reinforced concrete (such as "tilt-up" walls), and/or (3) reinforced brick masonry, and/or (4) reinforced hollow concrete block masonry. Floors and roofs may be of wood, metal, poured-in-place concrete, precast concrete, or other material. Interior bearing walls must be of wood frame or any one of a combination of the aforementioned wall materials. |
| 5B | Buildings having load bearing walls of unreinforced brick or other types of unreinforced solid unit masonry, excluding adobe. |
| 5C | Buildings having load bearing walls of hollow tile or other hollow unit masonry construction, adobe, and cavity wall construction. Also included are buildings not covered by any other class. |
| | **Earthquake Resistive Construction** |
| 6 | Any building with any combination of materials so designed and constructed as to highly earthquake resistant and *also* with superior damage control features in addition to the minimum requirements of building codes. |

Table 1 Continued

| Class | Description |
| --- | --- |
| | Miscellaneous |
| | Bridges, tunnels, dams, piers, wharves, tanks, tank contents, towers of all types, and the like. |

Source: Adapted from California Department of Insurance, *California Earthquake Zoning and Probable Maximum Loss Evaluation Program*. Los Angeles, California: California Department of Insurance, June 1986.

# APPENDIX E

# EARTHQUAKE WARNING SYSTEM

# SURVEY METHODOLOGY

# Appendix E

## Earthquake Warning Survey Methodology

Chapter 1492 specifies that this feasibility study include the:

"(3) Technical and economic feasibility of implementing the early warning system. Possible applications include automated shutdown of pipelines, transportation systems, computer systems, and other vital lifelines which would be damaged in an earthquake.

"(4) Assessment of the value of warnings to various elements of society, including public officials, schools, hospitals, police, fire stations, private industry, critical defense contractors, and gas, oil, and electrical industries. The assessment should include an estimate of the value of a warning as a function of the warning time and its reliability."

Because the effectiveness of an EWS depends on the acceptance of and participation in the system by users, we have attempted to make the feasibility study as "user-driven" as possible. That is, data collection on respondents' desires and interests has preceded any substantial design effort, in an effort to tailor the final system to the needs of the respondents contacted.

To do this, a survey questionnaire was selected as the primary means to collect information from potential EWS users on their earthquake risk, specific facility characteristics, and the applicability of an EWS to the facility's operations. Specifically, the survey was designed to answer the following questions.

- Who can benefit from an EWS providing from a few seconds to several tens of seconds of warning before the onset of damaging ground shaking?
- What are the potential uses of an EWS?
- What are the perceived costs/benefits of an EWS? This would include such items as the reduction of damages and injuries, false alarm consequences and costs to users, willingness to pay for EWS as a service, and possible intangible benefits of the EWS such as earthquake awareness, post-event earthquake information, and data for earthquake research.

We determined that a survey organizations with individuals knowledgeable on earthquake hazards was necessary to collect information on the organization-specific data on potential uses of an EWS. An expert survey depends on the objective, knowledgeable, and reasoned judgment of personnel familiar with their facility's operations rather than the subjective and immediate responses given in public opinion polls. In our survey, we addressed our inquiry to engineers, emergency responders, safety officers, and risk management personnel within each organization. We relied on the organizations to identify the personnel best qualified to respond to our survey.

In the case of an expert survey, the survey instrument must be carefully designed and the sample drawn from a representative group. Since an expert survey depends on objective and reasoned judgment rather than extemporaneous opinions, the sampling and survey techniques need not be as precise or as rigorously implemented as opinion polls. The objective with expert polls is to gather responses with greater depth and quality. We believe that organizational experts are the best sources of data on the applications, costs, and benefits that an EWS could provide their for facilities.

### Methodology for Selecting Users

Chapter 1492 specifies the potential users and applications of an EWS to be evaluated. In addition, we asked representatives of various state agencies to participate in a brainstorming session using the Nominal Group Technique to identify other potential users/uses of an EWS. Participants at the meeting included representatives from the Office of the State Architect, departments of Water Resources and General Services, the Office of Emergency Services, Seismic Safety Commission, and the Division of Mines and Geology in the Department of Conservation. As a result of this procedure, 45 separate ideas on the potential uses of an EWS were generated by the participants. These ideas, which encompassed the requirements of Chapter 1492, provided project staff with a variety of potential users/uses for an earthquake warning system. These ideas were then incorporated in the survey sample. The sample of potential users was selected based on the location and relative size of organizations within the user groups.

### Location

The sample was drawn from the study area including 15 counties of southern and central California: Fresno, Imperial, Kern, Kings, Los Angeles, Monterey, Orange, Riverside, San Benito, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Tulare, and Ventura. This study area includes all counties likely to be affected by strong ground motion from a major earthquake on the southern San Andreas fault. Although the organizations sampled are located in the study area, it was impossible to know, before the completion of the survey, the actual location of facilities that would be included in the survey by the respondents. In addition, the mailing address of the organization contact may be physically dissociated from operational facilities. Thus, it was necessary, after the surveys had been collected, to ensure that the responses reflected the geography of the study area.

### Relative Size

A sampling of the universe of potential users was used to select the most important participants in each user group, based on their relative size within the group. In general, schools with the greatest enrollment, hospitals with the largest number of licensed bed-days, and manufacturers with the largest revenues were selected. We chose to sample "large" users because:

- the potential economic impact of earthquake damage to large facilities are likely to be greater,

- large organizations are more likely to have the in-house expertise to respond to the survey,

- by their nature, large organizations are more likely than smaller organizations to have systems or equipment that could respond to a warning,

- Large organizations are also more likely to have the financial resources neccessary to subassemble an EWS.

When it was necessary to provide geographic balance to the sample, potential users in a group were selected on the basis of location as well as their relative size.

**Silicon Valley Survey**

In addition to the 15-county study area, a limited survey of high technology firms in the Silicon Valley was conducted. The purpose of the narrower study was to determine whether the unique manufacturing conditions found in Silicon Valley would support the use of an EWS. While the larger survey effort focussed on various uses in a 15-county region, this effort polled only industrial facilities typical of the Silicon Valley. Thus, other potential users such as fire and police services, public utilities, and the like were not surveyed in the Silicon Valley. The survey instrument and methodology however, were identical to the larger survey in every other aspect.

The 15-county sample includes 164 potential users of various types, 132 of types specified by Chapter 1492 and 32 others. The Silicon Valley survey includes four computer-related organizations. Table E.1 contains a listing of these groups.

**Development of Survey Instrument**

The main objectives of the survey were to identify the potential users and uses of an EWS. Moreover, the survey was intended to provide specific information on the costs and benefits that such a system imposes on users and whether and how much such users will pay for an EWS warning. The guiding legislation specified that this feasibility study focus on those potential uses of an EWS that mitigate earthquake damage to a facility's operations.

Because this inquiry involves careful consideration of how a complex system affects a facility's operations, the survey and associated information were necessarily demanding of respondents. We believe that a simple survey with binary and multiple choice responses would probably have oversimplified the results or inadequately addressed the most important questions. In the survey, we asked detailed questions on the facility, respondent's perception of earthquake risk, and potential uses of an EWS. In addition, questions were used to (1) ascertain the consistency and quality of responses, and (2) make inferences about earthquake risk and warning considerations for respondents. The survey was developed to flow from questions regarding a facility's earthquake risk and specific operations-at-risk to the uses and consequences of warning. To assist respondents in completing the survey, we provided, along with the survey, an information packet on earthquake risk in southern California, a description of the survey effort, and the nature and limitations of an EWS, plus a technical appendix which detailed earthquake risk and warning information. To elicit a greater response, the survey mailing included a cover letter requesting participation in the survey by the Acting State Geologist. (The cover letter, survey, information packet, and technical appendix are included in Appendix D.)

**Table E.1**

**Sample of Potential Users and Survey Response, by Legislative Requirement and Business Type**

| Potential Users/Uses Specified by Chapter 1492 | Number Sampled | Number Responses | Percent Responding |
|---|---|---|---|
| Computer Systems | 2 | 1 | 50 |
| Defense-Related Industry | 7 | 2 | 29 |
| Gas, Oil, & Electrical Industries | 21 | 13 | 62 |
| Hospitals | 7 | 2 | 29 |
| Other Vital Lifelines | 17 | 12 | 71 |
| Pipelines | 3 | 0 | 0 |
| Police & Fire Services (includes emergency services) | 21 | 11 | 52 |
| Private Industry (manufacturing) | 15 | 6 | 40 |
| Public Officials | 11 | 5 | 45 |
| Schools | 8 | 7 | 88 |
| Transportation Systems | 20 | 7 | 40 |
| Subtotal | 132 | 66 | 50 |
| **Other Potential Users/Uses** | | | |
| Banking and Finance | 9 | 3 | 33 |
| Insurance | 5 | 0 | 0 |
| Recreation/Entertainment Industries | 4 | 1 | 25 |
| Various Others | 14 | 6 | 43 |
| Subtotal | 32 | 10 | 31 |
| **Silicon Valley Applications** | | | |
| Computer-Related Manufacturing | 4 | 4 | 100 |
| Totals | 168 | 80 | 48 |

## Survey Design

The final design of the survey instrument was based on:

- *The necessary content of the survey.* The survey requested responses for average or typical facilities that best represent each facility type operated within the study area by the respondent organization. Information was requested in three major areas:

- Facility Data. Included questions on property insurance and on the construction characteristics, size, and value of the facility.

- Earthquake Risk. Included questions on seismic design criteria and reinforcement.

- Potential Uses, Consequences, Costs and Benefits of an EWS. Included questions on the vulnerable areas, operations and systems, uses for warning, necessary warning times, false alarm consequences, willingness to pay for an EWS, and general comments on an EWS.

• *Review of the survey and the associated information materials.* Prior to initiating the survey, the cover letter, survey, and information packet were reviewed by personnel in the United States Geological Survey, the California Seismic Safety Commission, consulting earthquake engineers, marketing personnel, and others. The input received from these reviewers was incorporated in the final survey.

• *Pretesting the survey on test respondents.* The survey and associated materials were pretested on eight different potential users. The pretest indicated that the survey response times would be longer than originally anticipated (generally greater than one month).

### Method of Contacting Potential Users

In order to facilitate greater response by potential users, the survey included numerous telephone contacts, a survey mailing, and personal visits with a portion of the sample.

Potential users were called by project staff to elicit their response to the EWS survey. When called, project staff used a written protocol for explaining the purpose of the call and requesting their participation in the survey. Each potential user was told that their responses would be kept strictly confidential by the State Geologist. If potential users agreed to participate, a survey packet was mailed to participants generally within two weeks of the initial telephone contact. The survey packet also indicated to participants that their responses would be kept confidential. In some cases, personal interviews were conducted with the participants.

Approximately two weeks after the survey was mailed to participants, project staff called the participants to ascertain whether (1) the survey had been received, (2) there were any questions regarding the material, and (3) a personal interview should be scheduled to clarify the potential user's answers. Project staff frequently called potential users several times to inquire on their progress and to elicit a greater response rate from participants. Finally, a portion of the respondents were interviewed to (1) increase the rate of returned surveys, (2) clarify the respondent's answers, and (3) validate the effectiveness of the surveys.

## Survey Response

As shown in Table E.1, 80 users (48 percent) of the 168 potential users contacted had returned 121 surveys, as of August 31, 1988. Of the 121 surveys, eight surveys were completed for facilities that were either not within the study area or did not describe specific facilities. The geographic locations of study area facilities identified by the respondents are shown in Figure E.1.

There were 22 nonrespondents (13 percent)–organizations that were contacted but which refused to participate either after the initial phone call or after receiving the survey. A small number (8) of the sample represented organizations which were not able to respond either because the organization (1) did not have facilities in the study area, (2) had recently undergone organizational changes such as the sale of its operations, or (3) was not the appropriate entity to respond to the survey. Fifty-eight organizations of the 168 sampled (35 percent) did not respond to the survey nor indicate an unwillingness to participate. A couple of respondents provided responses in the form of letters but did not complete the survey questionnaire.

## Overall Assessment of Survey

In general, the purpose of the survey was well received by respondents. Some of the respondents, however, were unfamiliar with the technical questions included in the survey. As a result, very few respondents provided data on the seismic response or characteristics of their facilities. Fortunately, this information was not critical in evaluating the question of uses, costs, and benefits of an EWS.

Surprisingly, fewer of the respondents were concerned with confidentiality of the data than we had anticipated. Apparently, the project team's pledge to maintain the confidentiality of the respondents' data was credible. Many of the respondents viewed the effort to evaluate an EWS as important whether or not they had a particular use for an EWS.

Answers to the question on the estimated savings/avoided losses and false alarm costs, were frequently incomplete. Many respondents indicated areas that could use a brief warning but would not–or were not able to–provide estimated values of the costs and benefits of a system. This may be because the survey asked respondents to estimate damages, damage mitigation by an EWS, and false alarm consequences for a hypothetical earthquake of uncertain magnitude and consequences. Estimating such data is extremely difficult and uncertain even when the magnitude and location of the earthquake is specifically identified. Thus, it is likely that few respondents felt they could adequately answer these questions. In addition, many respondents did not or could not–perhaps as a result of the uncertain consequences, costs, and benefits of an EWS–indicate an amount they would be willing to pay for an EWS if offered on a subscription basis. It is also possible that respondents do not feel comfortable revealing their willingness to pay before such a system is in operation or is proven effective.

Taken together, the problem in compiling and analyzing the survey responses lies more in the interpretation of qualitative responses than in tabulating and performing mathematical operations on the data. A simple-minded reading of the survey responses could result in a deficient or erroneous assessment of the feasibility of an EWS. Nevertheless, the data received from the survey represents the most complete set of information on the potential uses and consequences of an EWS for a broad range of users. On this basis, we will report on our analysis of the answers given by the respondents in Appendix F.

# APPENDIX F

# EARTHQUAKE WARNING SYSTEM

# SURVEY RESULTS

# APPENDIX F

## EARTHQUAKE WARNING SURVEY RESULTS

As mentioned in Appendix E, the survey effort yielded 121 surveys, each survey describing a facility. Of the 121 surveys, 113 identified specific facilities within the 15-county study area (109) or the Silicon Valley (4). This appendix summarizes the results received from the survey. Chapters in the main text of this report analyze and apply the survey results to the question of the feasibility and value of an EWS.

Some of the general characteristics of all survey respondents are presented first. We then discuss the indicated uses for an earthquake warning of between 1 and 120 seconds. In addition, the desired warning times, benefits, and costs identified by participants are given.

### General Characteristics of Respondents

As shown in the previous appendix, the respondents fairly represented the geography of the study area, as well as the facility types specified by Chapter 1492. Table F.1 contains a summary of the general identifying characteristics of the respondents. The responses included 80 critical facilities (based on the California Seismic Safety Commission definition), equivalent to 66 percent of all surveys. Many of the organizations have multiple facilities within the county where the survey facility is located and in the study area.

More than 85 percent indicated that the threat of an earthquake to their facility is "extremely important" or " very important." A significant number of respondents (41 percent) indicated that they have undertaken seismic reinforcing and many of their facilities (31 percent) were designed with specific seismic hazards in mind. Approximately 20 percent of the respondents carry earthquake insurance and 46 percent carry fire insurance. The predominant construction types included in the responses are reinforced concrete (21 percent), steel frame (15 percent), and mixed construction (12 percent).

### Respondents Indicating a Use for Earthquake Warning

Forty-four (36 percent) of the 121 surveys returned indicated 82 separate uses for an earthquake warning between 1 and 120 seconds. Thus, many respondents indicated more than one use for an EWS. The characteristics of those facilities having a use for earthquake warning are shown in Table F.2.

Table F.1

General Characteristics of Facilities Identified in 121 Survey Responses

| Characteristics | Number | Percentage of Respondents |
|---|---|---|
| Critical Facilities | 80 | 66 |
| Mean Number of Facilities Owned by Respondent in | | |
| County | 24 | – |
| Study Area | 41 | – |
| Threat of Earthquake Viewed as | | |
| Extremely important | 86 | 71 |
| Very important | 18 | 15 |
| Important | 8 | 7 |
| Slightly important | 2 | 2 |
| No response | 7 | 6 |
| Totals | 121 | 100 |
| Carry Earthquake Insurance | 24 | 20 |
| Carry Fire Insurance | 54 | 46 |
| Construction Types | | |
| Wood frame | 15 | 8 |
| All metal | 14 | 7 |
| Steel frame | 30 | 15 |
| Reinforced concrete | 42 | 21 |
| Mixed construction | 24 | 12 |
| Earthquake resistive | 15 | 8 |
| Miscellaneous | 18 | 9 |
| All types | 1 | 1 |
| Unspecified | 38 | 19 |
| Totals | 197 | 100 |
| Seismic Reinforcing Undertaken | 50 | 41 |
| Facility Designed for Specific Earthquakes | 37 | 31 |

## Table F.2

### General Characteristics of 44 Respondents Indicating a Use for Earthquake Warning

| Characteristics | Number | Percentage of Respondents |
|---|---|---|
| Critical Facilities | 26 | 60 |
| Facilities Owned by Respondent in | | |
| County | 27 | – |
| Study Area | 29 | – |
| Threat of Earthquake Viewed as | | |
| Extremely important | 30 | 68 |
| Very important | 7 | 16 |
| Important | 4 | 9 |
| Slightly important | 1 | 2 |
| No response | 2 | 5 |
| Totals | 44 | 100 |
| Carry Earthquake Insurance | 12 | 27F |
| Carry Fire Insurance | 25 | 57 |
| Construction Types | | |
| Wood frame | 7 | 9 |
| All metal | 7 | 9 |
| Steel frame | 13 | 16 |
| Reinforced concrete | 18 | 22 |
| Mixed construction | 11 | 14 |
| Earthquake resistive | 4 | 5 |
| Miscellaneous | 7 | 9 |
| All types | 1 | 1 |
| Unspecified | 13 | 16 |
| Totals | 82 | 100 |
| Seismic Reinforcing Undertaken | 16 | 36 |
| Facility Designed for Certain Earthquakes | 13 | 30 |

## Applications and Warning Times

The 82 separate uses identified by these respondents may be grouped according to four categories (see Appendix E for a complete listing of these uses by category and warning time):

- *Computer* uses include the shutdown of computer systems and disk drives or switching to emergency power.

- *Facility* applications include switching plant site power or natural gas and opening doors to remove fire fighting equipment prior to strong ground shaking. This category also includes the automatic disconnection of power to railroad lines, thereby stopping trains.

- *Personnel* responses range from evacuating buildings to activating employee response plans. Often these responses were not specific as to the actual personnel-related use of the EWS.

- *Production* applications represent a diverse set of uses of an EWS. This category includes diverting arriving aircraft, the shutdown of pipeline transfer operations and the controlled shutdown of test equipment and various production processes.

As shown in Figure F.1, the majority of uses in each category, according to respondents, require between 60 and 120 seconds to effect mitigating action. The mean and median warning times indicated were 72 and 60 seconds, respectively. The survey results indicate that 70 percent of the EWS users require at least 60 seconds of warning; 74 percent require more than 30 seconds. Thus, only about 26 percent of the EWS users desire warnings of 30 seconds or less. In effect, the uses are lumped around the half minute, minute and two minute levels of warning time.

The predominant applications of an EWS are for production-related processes and activities. Approximately 39 percent indicated that a warning for these applications would be useful. Another 23 percent cited the personnel uses for an EWS while computers and facilities were cited for 20 and 18 percent, respectively.

In general, all EWS uses were represented among the various warning times, Personnel applications, however, were *least* represented among uses with warning times of 30 seconds or less, reflecting the time needed to evacuate building areas. Computer and production applications represent nearly two-thirds of responses for the short warning times (30 seconds or less), perhaps reflecting the availability and use of switching equipment to effect action.

**Long Warning Times (60-120 seconds).** Although it is possible to conceive of uses for warning that take short amounts of time (10 seconds or less), very few respondents indicated a use or desire for such short times. We believe that there are at least three reasons for respondents to desire longer warning times. First, many respondents appear to be reluctant to delegate a shutdown decision to automated equipment, thereby removing humans from the decision process. In some cases, a false alarm could be extremely costly–and dangerous–to potential users.

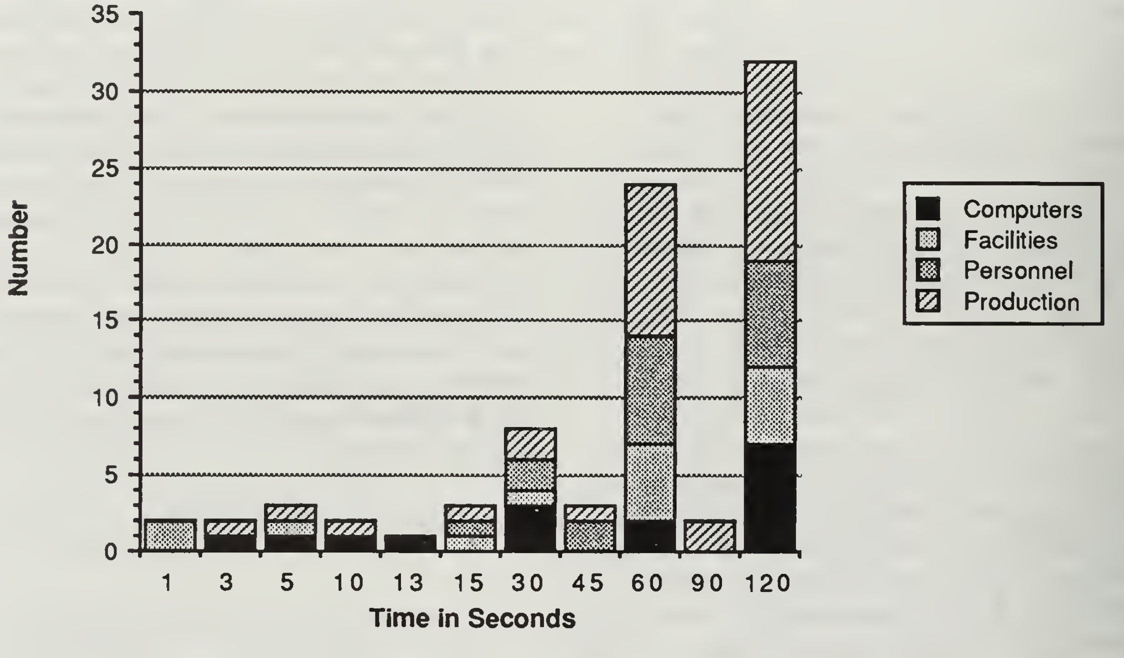
Second, major facilities contain large equipment and systems that are not easily or quickly shutdown. For example, large valves used in gas, oil, and water delivery systems frequently take minutes to open or close. Thus, the minimum times to take action on major systems are likely to be long. In addition, although an earthquake warning could initiate (if not complete) a damage mitigation process for major systems prior to strong shaking, potential users may wish to confirm the event before mitigating action is taken. Finally, the personnel uses for warning given by respondents generally included evacuation of buildings, which requires relatively long warning times. An earthquake warning system, however, could not guarantee sufficient time to effect such actions. We note that there are other personnel response actions such as crawling under a desk or getting away from windows which require only a few seconds and could therefore be effected by a warning.

**Short Warning Times (1-30 seconds).** As indicated in Figure F.1, 21 uses (26 percent) required warning times of 30 seconds or less. Three interesting uses for a short earthquake warning include

- diverting arriving aircraft by airport ground control (3 seconds),
- automatically disconnecting the power from railroad lines (15 seconds), and
- a controlled shutdown of a fire department's computer-aided dispatch system (30 seconds).

Other uses ranged from personnel response to computer-related and facility operations actions. Some of these uses, however, may have limited utility. For example, two uses involve disengaging the natural gas and electrical power supply at a manufacturing facility if given one second of warning. The respondent estimates that a major conflagration may be averted by taking these actions. If in fact only one second is necessary to effect these actions, a local on-site trigger may be more effective. Other short warning time uses that are of dubious benefit include shutting down personal computers and energy management systems. (We note that Silicon Valley respondents would have even less available warning time from a nearby event than respondents affected by events along the southern San Andreas fault.)

**Figure F.1**
**Types of Uses and Desired Warning Times**
**Survey of Large Organizations**




| Times | Computers | Facilities | Personnel | Production | Totals | Percent* |
|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 0 | 0 | 2 | 2 |
| 3 | 1 | 0 | 0 | 1 | 2 | 2 |
| 5 | 1 | 1 | 0 | 1 | 3 | 4 |
| 10 | 1 | 0 | 0 | 1 | 2 | 2 |
| 13 | 1 | 0 | 0 | 0 | 1 | 1 |
| 15 | 0 | 1 | 1 | 1 | 3 | 4 |
| 30 | 3 | 1 | 2 | 2 | 8 | 10 |
| 45 | 0 | 0 | 2 | 1 | 3 | 4 |
| 60 | 2 | 5 | 7 | 10 | 24 | 29 |
| 90 | 0 | 0 | 0 | 2 | 2 | 2 |
| 120 | 7 | 5 | 7 | 13 | 32 | 39 |
| Totals | 16 | 15 | 19 | 32 | 82 | 100 |
| Percentage* | 20 | 18 | 23 | 39 | 100 | |

* Percent totals may not sum due to rounding.

## Estimated Savings and Costs of False Alarms

The survey respondents were asked to estimate the savings (or avoided losses) that an earthquake warning might provide to their facility. In addition, respondents were asked to identify the consequences and estimate the costs of a false earthquake warning (EWS issues a warning, but no damaging earthquake occurs). These results only reflect those responses that indicated a use for a warning times of less than 120 seconds.

Out of 82 identified uses for an EWS, respondents reported the estimated savings as follows (see Table F.3):

- 14 (17 percent) reported savings ranging between $5,000 and $30 million. The mean and median of the 14 estimated savings responses are $4,635,000 and $1 million, respectively.

- 32 (39 percent) gave no dollar amount as savings.

- 36 (44 percent) responded that the savings were "unknown."

Less than one-fifth of the EWS users indicated specific dollar amounts in response to the estimated savings question. Although the balance (83 percent) of the responses did not include specific dollar amounts, we cannot assume that these responses are equivalent to zero. As noted in the previous chapter, the lack of specific responses is probably related to the difficulty in estimating such savings under the considerable uncertainty associated with earthquake damage. Thus, while we cannot safely assume that the average reported savings are representative of all EWS users, we also cannot estimate savings from the nonspecific or "unknown" responses.

Of the 82 identified uses, respondents reported the false alarm costs as follows:

- 18 (22 percent) reported costs between zero dollars and $1 million. The mean and median of the 18 false alarm responses were $67,000 and $1,000, respectively.

- 47 (57 percent) gave no dollar amount as costs.

- 17 (21 percent) responded that the costs were "unknown."

Again, only about one-fifth of the respondents gave specific dollar amounts to the false alarm costs question. In this case, many more of the respondents gave no dollar amount than with the estimated savings question while fewer responded that the costs were "unknown." Once again, while we cannot safely assume that the reported false alarm costs are representative of all EWS users, we also cannot infer these costs from the nonspecific responses. We note that nearly half of the responses indicate false alarm costs of zero dollars.

## Subscription Amounts

Respondents were asked what amount they would be willing to pay for each use they identified for an EWS if the warning were (1) 100 percent reliable and (2) 50 percent reliable (a warning is received for only 50 percent of the damaging earthquakes). Out of 82 EWS uses, the following willingness to pay at the 100 percent reliability level was indicated:

- 20 (24 percent) reported subscription amounts between $300 and $120,000 per year. The mean and median annual subscription amounts (20 responses) at the 100 percent level are $14,700 and $6,000, respectively.

- 58 (71 percent) gave no dollar amount.

- 4 (5 percent) responded that the amount they would pay is "unknown."

The problem of nonspecific or "unknown" responses to the question of subscription amounts is similar but not equivalent to such responses for the estimated savings and false alarm costs. While the subscription amount that an organization is willing to pay for an EWS should be directly related to economic benefits of receiving a warning, other factors are important. For example, an organization could elect to have an EWS simply to be kept informed or "just in case" it reduces

**Table F.3**

**Estimated Savings and False Alarm Costs Reported by 44 Survey Respondents Indicating a Use for an Earthquake Warning System**

| | Number | Range | Mean | Median |
|---|---|---|---|---|
| **Estimated Savings:** | | | | |
| Reported amount | 14 | $5,000-$30 million | $4.6 million | $1 million |
| No amount given | 32 | – | – | – |
| "Unknown" | 36 | – | – | – |
| **False Alarm Costs:** | | | | |
| Reported amount | 18 | $0-$1 million | $67,000 | $1,000 |
| No amount given | 47 | – | – | – |
| "Unknown" | 17 | – | – | – |
| **Subscription Amount If:** | | | | |
| 100 percent reliable | | | | |
| Reported amount | 20 | $300-$120,000 | $14,700 | $6,000 |
| No amount given | 58 | – | – | – |
| "Unknown" | 4 | – | – | – |
| 50 percent reliable | | | | |
| Reported amount | 12 | $300-$12,000 | $2,400 | $600 |
| No amount given | 69 | – | – | – |
| "Unknown" | 1 | – | – | – |

injury or damages. In these instances, an organization can estimate what it might be worth on a subscription basis to have this additional non-economic benefit. In addition, it may be easier to assign a value to the benefit of a potential for reducing risk than it is to estimate the damages that may result from an earthquake. Thus, while there were only 14 responses which included specific estimated savings, there are 20 responses that indicate a specific subscription amount, if the EWS is 100 percent reliable.

Out of 82 EWS uses, the following willingness to pay at the 50 percent reliability level was reported:

- 12 (15 percent) reported subscription amounts between $300 and $12,000 per year. The mean and median annual subscription amounts (12 responses) at the 50 percent level are $2,400 and $600, respectively.

- 69 (84 percent) gave no dollar amount.

- 1 (1 percent) responded that the amount they would pay is "unknown."

Not unexpectedly, fewer respondents are willing to pay for an EWS that only warns on 50 percent of the damaging earthquakes. Those that are willing to pay for the 50 percent system will pay much less than 50 percent of the amount they are willing to pay for the 100 percent system. In fact, several respondents indicated that a system that was 50 percent reliable was no help whatsoever, thus they would be unwilling to pay *any* amount for it.

## Summary and Conclusions

The survey results indicate that 44 (36 percent) of the 121 returned surveys identified at least one use for an earthquake warning between 1 and 120 seconds prior to strong shaking. A total of 82 uses were identified. This response, in itself, indicates that there is an interest in and desire for some type of earthquake warning system.

Of those respondents indicating a use for an EWS, they generally

- Desire long warning times (greater than 30 seconds).

- View the EWS as useful for mitigating damage in the categories of production (39 percent), personnel (23 percent), computers (20 percent), and facilities (18 percent).

- Did not give or know what their estimated savings would be as a result of an EWS. Those who provided a specific response (17 percent of respondents) estimated their savings to be between $5,000 and $30 million. The mean and median estimated savings of those providing a specific response are $4.6 million and $1 million, respectively.

- Did not give or know what their false alarm costs would be as a result of an EWS. Those who provided a specific response (22 percent of respondents) estimated their false alarm costs between zero dollars and $1 million. The mean and median false alarm costs of those providing a specific response are

$67,000 and $1,000, respectively.

- Did not give or know what they would be willing to pay to subscribe to an EWS. Those giving a specific response (24 percent) indicated that they would pay between $300 and $120,000 per year for a 100 percent reliable system. Fifteen percent would pay between $300 and $12,000 for a 50 percent reliable system.

Based on these results, we conclude that there is interest in an earthquake warning system that provides between 1 and 120 seconds of warning. The economic merits of an earthquake warning system for potential users and society as a whole, however, are less clear. Although the mean and median estimated savings are large relative to the mean and median false alarm costs, it is not clear whether any of these amounts suitably represent all respondents indicating a use for an earthquake warning. Moreover, the mean and median amount respondents are willing to pay for a 100 percent reliable system is much less than the estimated savings the respondents expect, even when accumulated over the expected 25 year life of the system. A more detailed analysis of the economic considerations associated with such a system is included in Chapter Six.

# APPENDIX G

## WARNING USES/AREAS BY TIME AND CATEGORY OF USE,

## INDIVIDUAL RESPONSES FROM SURVEY

# APPENDIX G

## Warning Uses/Areas, Times and Use Categories, Individual Responses from Survey

| Warning Uses/Areas | Seconds Desired | Category of Use |
|---|---|---|
| Natural Gas | 1 | Facilities |
| Plant Site Power | 1 | Facilities |
| Disk Drives | 3 | Computers |
| Arriving aircraft coud be alerted by Localizer voice or ground control to divert landing | 3 | Production |
| Personal computers could be shut down in a few seconds | 5 | Computers |
| Energy management computer could shut-down lights, air conditioning units, and electrical motors | 5 | Facilities |
| Laser could be shut off manually | 5 | Production |
| Computer | 10 | Computers |
| Animals would be secured | 10 | Production |
| Computer Center | 13 | Computers |
| Transit Operations-Power disconnect | 15 | Facilities |
| Office Building | 15 | Personnel |
| Garage Area (Maintenance) | 15 | Production |
| Computer Aided Dispatch System (CAD) | 30 | Computers |
| Computer Heads | 30 | Computers |
| Mini Computer - Data | 30 | Computers |
| Plant Control Rooms | 30 | Facilities |
| Buses could be stopped | 30 | Personnel |
| Personnel | 30 | Personnel |
| Assembly Areas | 30 | Production |
| Reprographics | 30 | Production |
| Employee response plan | 45 | Personnel |
| Personnel | 45 | Personnel |
| Acetylene Filling | 45 | Production |
| Escondido - Shutdown Computer | 60 | Computers |
| Institutional Research & Automated Data Processing | 60 | Computers |
| All Mechanical & Electrical Systems | 60 | Facilities |
| Apparatus Doors opened, Apparatus and Personnel removed from quarters | 60 | Facilities |
| Diesel Generators | 60 | Facilities |
| Maintenance Buildings | 60 | Facilities |

# APPENDIX G

## Warning Uses/Areas, Times and Use Categories, Individual Responses from Survey

| Warning Uses/Areas | Seconds Desired | Category of Use |
|---|---|---|
| Shops/maintenance | 60 | Facilities |
| All living spaces | 60 | Personnel |
| Cafeteria | 60 | Personnel |
| Dining Hall | 60 | Personnel |
| House | 60 | Personnel |
| Library | 60 | Personnel |
| Office Areas | 60 | Personnel |
| Office Building | 60 | Personnel |
| Audio-Visual | 60 | Production |
| Burn-In | 60 | Production |
| Coil Coating | 60 | Production |
| Container Cranes-shut off power | 60 | Production |
| Crane operation | 60 | Production |
| Equipment | 60 | Production |
| Gas pad shutdown (in area of wafer fabrication) | 60 | Production |
| Plate Milling | 60 | Production |
| San Diego - Alvarado Hydro-Electric Plant | 60 | Production |
| San Diego - Miramar Hydro-Electric Plant | 60 | Production |
| Sludge Combustion | 90 | Production |
| Sludge Dewatering | 90 | Production |
| Computer | 120 | Computers |
| Computer Disk Drives | 120 | Computers |
| Computer software | 120 | Computers |
| Computers | 120 | Computers |
| Computers put in idle state | 120 | Computers |
| Shutdown of computer disk drives | 120 | Computers |
| Switch to emergency power, or shut down computer equipment | 120 | Computers |
| Bridges | 120 | Facilities |
| Fire Stations (Allow time to remove apparatus from stations) | 120 | Facilities |
| Heating, Ventilation, and Air Conditioning Systems | 120 | Facilities |

## APPENDIX G

### Warning Uses/Areas, Times and Use Categories, Individual Responses from Survey

| Warning Uses/Areas | Seconds Desired | Category of Use |
|---|---|---|
| Storage area | 120 | Facilities |
| Utility Systems | 120 | Facilities |
| Evacuation of people or under shelter | 120 | Personnel |
| Los Angeles General Office Building | 120 | Personnel |
| Offices-evacuate area | 120 | Personnel |
| Orderly evacuation of personnel | 120 | Personnel |
| Personnel safety | 120 | Personnel |
| Ponds-evacuate area | 120 | Personnel |
| Structural / evacuation | 120 | Personnel |
| Chemical Systems (Particularly Chlorine) | 120 | Production |
| Cogeneration | 120 | Production |
| Dross Recovery | 120 | Production |
| Fresno Dispatch Operations Center (Railroad) | 120 | Production |
| Gas Processing Facilities | 120 | Production |
| Melting/Casting | 120 | Production |
| Offshore Platform | 120 | Production |
| Oil and Gas Wells | 120 | Production |
| Pipelines-shutoff transfer operations | 120 | Production |
| Production | 120 | Production |
| San Bernardino Dispatch Operations Center (Railroad) | 120 | Production |
| Shut down of facility- films or sets | 120 | Production |
| Sludge Drying | 120 | Production |

# APPENDIX H

## SUMMARY OF EARTHQUAKE EXPERIENCE DATABASE RESULTS

## PROVIDED BY CONSULTANT TO DEPARTMENT OF CONSERVATION

APPENDIX H
SUMMARY OF EARTHQUAKE EXPERIENCE DATABASE RESULTS
PROVIDED BY CONSULTANT TO DEPARTMENT OF CONSERVATION

| FACILITY TYPE | TYPICAL EQUIPMENT INSTALLATIONS | DATABASE EARTHQUAKES | NO. OF OBS. | PGA (g) RANGE | TYPICAL EARTHQUAKE DAMAGE | IMPACT OF WARNING | CONSEQUENCE OF FALSE ALARM |
|---|---|---|---|---|---|---|---|
| Substations | Control and communication equipment-control panels, relay racks<br>Emergency DC power - batteries, battery chargers<br>Cable trays/conduit<br>Switchyard equipment (including brittle ceramics) - transformers, high voltage circuit breakers | 1971 San Fernando, M6.5<br>1978 Santa Barbara, M5.1<br>1983 Coalinga, M6.7<br>1984 Morgan Hill, M6.2<br>1985 Santiago, Chile, M7.8 and 7.2<br>1986 Adak, Alaska, M7.7 and 6.5<br>1986 North Palm Springs, M6.0<br>1986 San Salvador, El Salvador, M5.4<br>1986 Bay of Plenty, New Zealand, M6.2<br>1987 Whittier Hills, M5.9 | 4<br>1<br>2<br>1<br>3<br>1<br>1<br>2<br>2<br>4<br>21 | .15-.85 | Broken or leaking circuit breakers, lightening arresters.<br>Switchyard Transformers that have slid or fallen | Possible avoidance of electrical fires by tripping station | Potential to black out area served |
| Fossil Fuel Power Plants | Steel frame towers housing pendulum-supported boilers plus rod-hung piping, conduit, cable trays, large ductwork for forced air supply.<br>Steel framed turbine building with heavy concrete pedestals supporting turbine-generator & condensor.<br>Power supply to equipment et 4,160 and 480 volts through switchgear, motor control centers & substation transformers.<br>Mechanical systems include horizontal and vertical pumps ranging up to 500 hp, pneumatic and motor-operated valves, air compressors, furnace fans, heat exchangers, and tanks.<br>Large ground-supported storage tanks, a water treatment plant, and wooden cooling towers.<br>Power from generators is stepped up to 66 or 160 kV in nearby substations. | 1971 San Fernando, M6.5<br>1973 Point Mugu, M5.9<br>1975 Ferndale, M?<br>1978 Santa Barbara, M5.1<br>1979 Imperial Valley, M 6.8<br>1980 Eureka, M7.0<br>1985 Santiago, Chile, M7.8 and 7.2<br>1986 Adak, Alaska, M7.7 and 6.5<br>1987 Whittier Hills, M5.9<br>1987 Superstition Hills, M6.0 and 6.3 | 4<br>1<br>1<br>1<br>1<br>1<br>3<br>1<br>4<br>2<br>19 | .18-.42 | Plants usually tripped by operators during or following earthquake; however, plant may be tripped by relay ection.<br>Minor damage indicates sliding of unanchored equipment, damage to piping insulation, damage to pipe supports, minor structural damage.<br>Moderate damage indicates buckling/ yielding of steel boiler support structure, damage to equipment caused by differential movement, damage or stretching of anchor bolts, or leaking of pipes.<br>Experience data not availeble for major damage to a fossil fuel power plant. | Only use for warning would be for possible personnel safety. No advantage to tripping of plant.<br>Depressurizing steem boiler requires more than a few minutes, and data indicates that there has never been e failure of high pressure piping or vessels. | Perturbations to power grid, possibly resulting in blackouts. Shutdown may take several hours to return plant to operation. |
| Hydroelectric Power Plants | Typically housed in massive reinforced concrete substructure with steel frame high bay structure.<br>Hydroelectric generators with capacities from 20 to 75 MW.<br>Bridge cranes to allow maintance/access to generators.<br>Extensive piping, cable trays, and conduit.<br>Emergency power supplied using batteries battery chargers; sometimes small motor-generator is used.<br>Control and instrumentation systems are primarly pneumatic. In larger facilities a control building will include 4,160 and 480 volt switchgear as well as motor control centers and substation transformers.<br>Power from generators is stepped up to distribution voltages at an adjacent substation or switchyard. | 1979 Imperial Valley, M 6.6<br>1985 Santiago, Chile, M7.8 and 7.2<br>1985 Mexico City, Mexico, M8.1 and 7.5<br>1986 North Palm Springs, M6.0<br>1986 Chalfant Valley, M6.5 and 5.5<br>1986 Bay of Plenty, New Zealand, M6.2 | 1<br>1<br>2<br>1<br>2<br>1<br>8 | .14-.50 | Data indicates no major damage to hydroelectric facility.<br>Most severly damaged facility was the Rapel Hydroelectric Plant damaged in the 1985 Chile earthquake: ceramic components in adjacent switchyerd were damaged; one leg of one gantry crane jumped its rail; minor structural damage to dam; distortion of bus bars on the emergency batteries; minor sliding of electrical equipment in the control house; and damage to five protective relays in the control house. | No advantage to early warning other than possible personnel safety. By slowing generators, might avoid bearing failure; however, data does not indicate damage of this type | If false alarm triggered shutdown, result could be revenue loss, serious perturbetions of power grid, possibly leading to blackout. |

APPENDIX H

SUMMARY OF EARTHQUAKE EXPERIENCE DATABASE RESULTS
PROVIDED BY CONSULTANT TO DEPARTMENT OF CONSERVATION

| FACILITY TYPE | TYPICAL EQUIPMENT INSTALLATIONS | DATABASE EARTHQUAKES | NO. OF OBS. | PGA (g) RANGE | TYPICAL EARTHQUAKE DAMAGE | IMPACT OF WARNING | CONSEQUENCE OF FALSE ALARM |
|---|---|---|---|---|---|---|---|
| Water Treatment/ Pumping Stations | Several vertical deep well pumps.<br>Buried piping<br>Automatic valve actuators (both air- and motor-operated)<br>Electronic controls - unmanned pumping stations may have computerized controls.<br>Switchgear, motor control centers, substation transformers | 1983 Coalinga, M6.7<br>1985 Santiago, Chile, M7.8 and 7.2<br>1986 San Salvador, El Salvador, M5.4 | 4<br>2<br>1<br>7 | .20-.60 | Seismically-induced ground settlement often causes misalignment or binding of the pump shafts.<br>Breaks occur in underground piping. | In addition to personnel safety, the stopping or slowing of large rotating equipment may prevent the binding of pump shafts. | Since many facilities are unmanned, some effort would be required to restart the facility |
| Chemical/Oil Facilities and Tank Farms | Extensive piping systems, both aboveground and buried<br>Large ground-mounted tanks and heat exchangers<br>Control systems - including switchgear, motor control centers, substation transformers<br>Mechanical equipment - pumps, air compressors, remote valve actuators (air- and motor-operated)<br>Emergency power supplies - battery chargers | 1983 Coalinga, M6.7<br>1985 Santiago, Chile, M7.8 and 7.2 | 4<br>3<br>7 | .20-.60 | Damage to tanks and their contents either through inadequate anchorage or poor tank design<br>Sliding of unanchored equipment, stretched anchor bolts<br>Most severly damaged facility was the Getty Oil Facility in the 1983 Coalinga earthquake: one large oil storage tank suffered a leak; three large anchored oil heaters slid, pulling attached piping; anchored switchyard transformer slid, breaking electrical connections; two unanchored computer cabinets overturned; sliding of unanchored equipment in control building; suspended ceiling panels fell; minor structural damage; cracking and rupture in buried plastic conduit. | Possible reduction of fire hazard by depressurizing systems containing flammable substances (possibility would require study on a case-by-case basis). | Loss of revenue if facility shuts down, and required inspection to restart. |
| Factories/Mills | Larger factories often include their own power plant.<br>Conveyor systems to storage facilities<br>Large storage tanks<br>Large capacity bridge cranes<br>Solid state control equipment | 1985 Santiago, Chile, M7.8 and 7.2<br>1985 Mexico City, Mexico, M8.1 and 7.5<br>1986 San Salvador, El Salvador, M5.4<br>1986 Bay of Plenty, New Zealand, M6.2 | 2<br>2<br>1<br>5<br>10 | .25-1.0 | Misalignment of conveyor systems.<br>Spillage of warehouse contents (flour and paper).<br>Structural damage to unreinforced masonry buildings. | Stopping/slowing large rotating machinery (e.g., paper machines, steel rolling machines), may mitigate extensive damage to facilities and critical equipment. Warning might allow personnel time to stand clear of dangerous substances (molten solder/lead) and to clear buildings. | Potential loss of revenue during start-up of machinery. At one steel mill, a power failure caused once molten steel to solidify in vats, requiring days of cleanup time. |

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| FACILITY TYPE | TYPICAL EQUIPMENT INSTALLATIONS | DATABASE EARTHQUAKES | NO. OF OBS. | PGA (g) RANGE | TYPICAL EARTHQUAKE DAMAGE | IMPACT OF WARNING | CONSEQUENCE OF FALSE ALARM |
|---|---|---|---|---|---|---|---|
| Hospitals/Computer/ Research Facilities | HVAC equipment includes fans, chillers, air handlers and pumps.<br>Extensive piping and duct systems.<br>Power supply to the equipment through motor control centers, switchgear, and substation transformers.<br>Controls are typically electronic and may be computerized.<br>Emergency power supplied by diesel-generator or uninterruptable power supply (UPS - battery, charger, inverter). | 1971 San Fernando, M6.5<br>1984 Morgan Hill, M6.2<br>1985 Santiago, Chile, M7.8 and 7.2<br>1987 Whittier Hills, M5.9 | 1<br>4<br>2<br>3<br>10 | .20-.75 | HVAC vibration isolation mounts are notorious for failing in earthquakes. Another common cause of damage to HVAC equipment comes from anchor point displacement (an unanchored boiler will move, pulling and damaging attached equipment).<br>"Computer floors" have slid and tipped during earthquakes.<br>The Ticor Facility, damaged in the 1987 Whittier earthquake, was the most severly damaged computer facility in the data base: anchored equipment in penthouse pulled/sheared anchorage; equipment on isolation mounts, damaged anchorage; structural damage to tilt-up panel joints; facility down for 8 months. | Computer facilities generally have backup power supplies (UPS, batteries, diesel generators), which operate automatically in the event of power loss. Experience data indicates that the emergency back-up systems have never failed to operate during/following an earthquake. Minor advantage of warning would be to save work in progress, thereby avoiding the expense of having to recreate work that was lost. | No impact |
| TOTAL FACILITIES | — | 17 different earthquakes, worldwide, M5.1-8.1. Includes 12 different California earthquakes, M5.1-7.0 (48 observations). | 82 | .14-1.0 | — | — | — |

# APPENDIX I

## EARTHQUAKE WARNING SYSTEM OPTIONS AND COSTS

# APPENDIX I

## EARTHQUAKE WARNING SYSTEM OPTIONS AND COSTS

### Introduction

The primary goal of an EWS ground-motion-monitoring and communications network is to provide earthquake data to the decision-making warning computer (or the user), at a speed such that users can benefit from the time between the warning and the onset time of strong ground motion.

In this appendix, we consider the technical options and costs associated with an earthquake warning system designed to monitor and collect data on critical fault segments and to provide useful warnings on potentially damaging earthquakes occurring along those fault segments. We identify systems and methodologies that could, under ideal conditions, provide usable warning times. For each system considered, a best estimate will be made of the system cost, warning time overhead, efficiency, and expected false alarm rate.

Only one of many possible design concepts for an earthquake warning system will be discussed: a system that detects an earthquake in the proximity of it's epicenter, and transmits sufficient information to allow a decision to warn. Other "warning" options, such as user-deployed (i.e., local to their site) ground-motion-trigger systems, may not provide "warning" in the strictest sense of the word, but may be of value to industries whose uses require very short response times and very low false alarm costs (see Chapter Five). Many such systems are already in use.

The technical aspects of earthquake warning differ considerably from those of the routine observatory practices of estimating earthquake location and magnitude on a regional basis. Observatory seismic stations are generally spaced many tens, and possibly hundreds, of kilometers apart. Earthquake locations are estimated from the relative arrival time of the seismic body waves, taking into account the distribution of seismic stations and the velocity structure of the Earth. Earthquake magnitudes are estimated by a variety of methods, but generally depend on the amplitudes of body- and/or surface-waves at regional and teleseismic distances. Methods that use longer period waves generally produce more precise estimates of the magnitudes of larger earthquakes.

Earthquake warning requires similar seismic information (approximate location and magnitude). However, a decision on the event occurrence, location, and magnitude must be made rapidly, using real-time data obtained in close proximity to the epicenter in order to provide a useful warning. This particular application of real-time seismology has never been attempted.

In the course of this study, we have identified several methods (algorithms) of earthquake warning. All of the methods require data from a relatively dense array of instruments (instruments spaced every 10-15 km) or dense arrays along targeted faults. The methods differ considerably in expense, sophistication, and reliability.

It is worth mentioning that no methodology exists that can reliably predict or warn for large or great earthquakes on the basis of strong motion data collected by a few instruments located only in the vicinity of the earthquake epicenter. Reliable warnings for large earthquakes require additional time until the earthquake is sufficiently developed. The alternative is to alarm on an earthquake in progress that may develop into a major event. Then, additional warnings (updated or secondary warnings) could be issued on the basis that the earthquake process has exceeded some criterion for size (e.g., magnitude, moment, rupture length). Only a few large California earthquakes have been recorded in close proximity to their rupture (e.g., Parkfield 1966, Imperial Valley 1979, and Morgan Hill 1986). For those faults being considered for a southern California EWS, little data has been recorded in close proximity to the rupture of a major earthquake. Consequently, the system reliability is difficult to estimate.

### Algorithms

**Peak Value exceedance.** Amplitudes of the high frequency earthquake ground motions grow approximately exponentially with the earthquake magnitude. A very approximate estimate of the earthquake size can be made from observations of the peak level of motion (acceleration) at a known distance from the earthquake. Thus, a warning could be issued based on the exceedance of a specified level of ground acceleration at one or more sensor locations close to the earthquake's epicenter. The method of using peak acceleration could be the least expensive and operationally the most reliable, but it provides the least amount of information on the earthquake. The original earthquake warning system of the Japanese Railway uses sensors that measure ground acceleration at sites near their railway. Upon exceedance of 0.15g acceleration, the system switches the power off on that segment of track. For a system based on this design, sensors may lie dormant until motion is sensed at a specified level, then transmit a simple (several-bit) message to a computer that monitors the system. This "extended trigger" system can be inexpensive. The communication system can also be relatively inexpensive and may incorporate a low data-rate but reliable satellite communications system similar to that used by the weather service (approximately $5,000/station).

While operationally reliable and inexpensive, a system based on peak ground motion values would provide the least reliable warnings because high frequency motions (peak ground acceleration) can be affected by a variety of parameters, most of which are difficult to evaluate. These parameters include the details of the fault rupture, the proximity of the sensors to the rupture, and the geologic characteristics of the earth's crust and the recording site. Consequently, the problem becomes one of earthquake magnitude discrimination, namely, how can the system distinguish a moderate (M4 or M5) earthquake from a large (M6 or M7). This uncertainty is a result of the stochastic nature of ground motion. That is, in the seismic near-field of earthquakes of M5 and greater, the peak ground accelerations are statistically independent of earthquake magnitude. The standard error for these peak ground motion regressions is approximately 50 percent of the mean value.

As an example of the practical problems of this procedure, consider a warning algorithm that would trigger on the exceedance of a specified level of motion. Assume that instruments are installed along a strike-slip fault every 10 km, approximately 2 km distant from the fault trace. For purposes of increased reliability, we require two adjacent instruments to register at least 0.3g within any 10 second interval before a warning can be issued. From the historic peak ground motion data compiled for southern California, we can expect that a magnitude 7 along this instrumented fault segment would have an 80 percent chance of triggering a warning. That is, there would be an 80 percent chance that 0.3g would be exceeded at the two sensor sites nearest the epicenter. Correspondingly, there would be a 20 percent chance that a hypothetical M7 would not generate 0.3g at both stations.

Consider the false alarm rate for the example above. Based on the historical occurrence of moderate to large earthquakes in southern California, for every magnitude 7 earthquake that has occurred, there are approximately 10 M6s and about 100 M5s that would be expected to occur over the same period of time. Of the 10 M6s, four of these earthquakes would produce motions greater than 0.3g at two instrument sites, and would trigger the same warning as the M7. Of the 100 M5s, approximately three could be expected to trigger warnings.

If we assume that the M7 occurs every 150 years, (similar to the recurrence rate along the Mojave segment of the San Andreas fault), these false alarms would occur at an average rate of one every 6 years. We note that the current seismicity along that segment of the San Andreas fault has a considerably lower rate. In order to improve the likelihood that the system would trigger on the M7, the peak ground motion threshold could be lowered. However, the system would then be subject to additional false alarms. In order to achieve greater confidence in this method, the system must trigger the warning based on exceedance of motions recorded at additional instruments further from the earthquake epicenter. Consequently, overhead time is increased and warning time is reduced. Added to these "earthquake-caused" false alarms would be the 1 or fewer false alarms per year that could result from equipment failure within the warning system (see Appendix B for a discussion of JR's false alarm rates.)

Instead of basing a warning on measured peak levels of acceleration, one could use the periods and amplitudes of peak displacement recorded near the causative fault. As observed by Aki (1968) and Toksoz (1987), the perpendicular component of motion adjacent to strike-slip faults is nearly always accompanied by a large shear-wave displacement pulse corresponding to the co-seismic fault rupture. This large pulse may be a more robust single station indicator of a large earthquake in progress than a method that uses only peak ground acceleration. An evaluation of this type of procedure, using large, long period, displacement pulses as a magnitude discriminator for earthquakes of moderate magnitude, would require additional study. This procedure may require the processing of seismic waveform data. Consequently, the system costs would be greater using this methodology than that using the peak ground acceleration approach.

**Current moment exceedance.** Toksoz, and others, (1987) and Toksoz and Dainty (1988) have proposed an algorithm for earthquake warning on highly-instrumented strike-slip faults. This method requires more sophisticated instrumentation and communications than that previously discussed, but may be the most reliable of the algorithms we have examined.

The algorithm estimates the seismic moment, $M_o$ (a measure of earthquake size), during the course of the earthquake. Seismic moment is defined by:

$$M_o = mu*w*L*d$$

where mu is the shear-modulus, w is the fault width (depth, for strike-slip faults), L is the rupture length, and d is the average slip over the faulted area. The shear-modulus is a known (measured) property of the fault. The fault width (depth) is assumed to be 12-15 km, the average rupture extent for major earthquakes in California. The average slip and length of rupture are estimated by the width (period) and amplitude of the large shear-wave displacement pulse accompanying the propagating fault rupture (Aki, 1968). The basic data collected is similar to the alternative described in the last section. However, more data processing is required to estimate the seismic moment as a function of time during the rupture process. An EWS using this algorithm would monitor the fault rupture until a specified $M_o$ is exceeded, at that time a warning is issued with an associated confidence in the current earthquake moment and magnitude.

Toksoz, and others (1988), tested the algorithm on strong motion data recorded during the 1984 Morgan Hill and 1979 Imperial Valley earthquakes. The resulting estimates of the events' seismic moments were within a factor of 2.5, equivalent to about four tenths of one magnitude unit, of the magnitudes determined after the events with all available data. The amount of time required for an M6 notification (i.e., that at least an M6 is occurring) was estimated to be about 5 seconds from the origin time; that is, about five seconds is necessary for the earthquake to develop a seismic moment equivalent to M6. Reliable notification of a magnitude 7 or greater earthquake in progress would take approximately an additional 10 seconds or so. It is difficult to estimate the uncertainty in the seismic moment computed by this method. Near-field S-wave observations are not available on the segments of the San Andreas of most interest. The uncertainty could be reduced by "calibrating" the system on smaller earthquakes.

The advantage of this approach is that the estimation of long-period quantities such as seismic moment, are not as influenced by local site effects as much as the higher frequency quantities, such as peak ground acceleration. The disadvantages of this method are the expense of the high quality instruments and the amount of time that is required to collect and process the data.

**Rate of change of P-wave moment.** Scheiner and McEvilly (1986) discussed a procedure that predicts earthquake magnitude from regional observations of the developing P-wave for western U.S. earthquakes. They noted that, for about M6.5 and less, the slope of the low frequency P-wave spectral amplitude versus time is proportional to local magnitude. Subsequent analysis of additional California earthquakes indicates considerable scatter and, thus, considerable uncertainty in the magnitude estimate, but a positive correlation still exists (Scheiner, personal communication). While this procedure requires the processing of wide-band digital data, the processing is considerably simpler than the method of current moment, described above. However, the method has never been tested with near-field data. Waiting for the P-waves to reach "regional" distances would add unacceptable overhead time.

### Summary of Algorithm Requirements

Table I.1 summarizes our estimated minimum system overhead times and the approximate reliability for the three warning algorithms discussed above. Each of the procedures assumes that instruments are spaced every 10 km along a strike-slip fault. The overhead time does not include any data communication or data processing time, and the reliability assumes that there are no computer, instrumentation, communication, or software failures.

Reliability is difficult to estimate because only limited amounts of seismic data have been recorded very close to earthquakes on major strike-slip faults. There is also a trade-off between reliability and warning time. More reliable estimates of predicted levels of motion and onset time are possible if warnings are delayed until additional data are collected by the system. One approach to increase reliability (at the expense of warning time) is to issue a multiple-level warning, with the initial warning based on data collected at the closest stations to the epicenter.

### Earthquake Warning System Configuration Options

In this section, warning system instrumentation options that would be suitable for one or more of the warning algorithms discussed above are examined. Configuration considerations include speed, reliability, and cost. The collection of seismic data in real-time is not a question of feasibility, but of cost. Because the design and construction of new (and sophisticated) seismic networks can be fraught with potential hardware and software problems, we consider only proven, available components. Other system configurations are possible. However, considerable additional effort may be required to insure that the components are compatible with one another.

The key factors affecting system cost are the number of remote sensors, the quality and amount of data collected, and the speed, reliability, and quantity of the data transmitted.

The fundamental requirement of the EWS is that it must not only survive the earthquake for which it is designed, but it must also operate to fullest capacity during the strongest ground motion. The loss of data from even one instrument could decrease warning time substantially. Consequently, consideration of existing communications systems, such as telephone and State microwave and fiber-optic systems, must be evaluated not only as potential communications options (including considerations of cost and dynamic range), but as viable facilities hardened to all natural phenomena (including earthquakes) that may affect system operation. Several seismic networks in the State routinely use leased telephone lines and microwave links to transmit seismic data. These systems have never experienced the magnitude of ground shaking and fault rupture expected in the next great California earthquake. Unless these systems are significantly hardened, partial failure of these systems seems certain (Davis and others, 1982).

**Table I.1**

**Estimated average warning overhead and reliability for earthquake warning algorithms**

| Algorithm | Warning Magnitude* | System Overhead (seconds)** | Magnitude Uncertainty | Estimated Reliability*** |
|---|---|---|---|---|
| Peak Ground a(t) | 6.0 | 5 | 1.0 | 20% |
| Peak Ground a(t) | 6.0 | 15 | 0.5 | 50% |
| Peak Ground d(t) | 6.0 | 5 | ? | ? |
| Real-time Mo | 6.0 | 10 | 0.25 | >50% |
| Real-time Mo | 7.0 | 20 | 0.25 | >50% |

* Warning magnitude is the target earthquake magnitude for issuing a warning. That is, warning is issued when the "current" magnitude exceeds this value.

** System overhead time, from origin time; assumes an instrument spacing of 10 km, the triggering of a least two instruments, and no data communications overhead.

*** System reliability is estimated assuming no failure of hardware or software, and considers earthquake occurrence on only instrumented portions of the fault (no false alarms caused by earthquakes on adjacent fault segments). The system is 50 percent reliable, for instance, if half of the warnings issued result from earthquakes with a magnitude greater than or equal to the "target" magnitude. The remainder would be smaller earthquakes.

Seismic data can be processed and evaluated for warning using any of a number of general system configurations. Computer systems located in proximity to the sensors can be used to detect earthquakes and to actuate the warning notification system, avoiding the time and expense of transmitting data to a central processing facility. Alternatively, all seismic data can be transmitted to a central processing facility, where warning decisions are made. These two approaches probably represent two extremes in cost because of the amount of information that must be rapidly transferred. A hybrid system could use field computers to derive summary observations such as arrival times, epicentral location, estimated shear-wave displacement and seismic moment. This summary data would be transmitted to the central processing facility for evaluation.

Each EWS warning algorithm has its own data processing time requirements. For example, delays are introduced while the system waits earthquake development (fault rupture extent or seismic moment to exceed a specific value) before a warning is triggered. During this time, however, users could receive a ground motion "advisory." Extensive computer processing time that could be required to evaluate seismic data would cause further delays.

It is possible for notification of users to be done on an individual need basis. The central computer of an EWS could have each EWS user's warning time and reliability needs stored in memory. As earthquake data is collected and interpreted, the computer would continuously sort the EWS users' needs and issue a warning in phases based on those needs. Thus, users requiring the most warning time with correspondingly the lowest reliability could be notified earlier. However, the continuous sorting and notifying could delay the issuance of warning to some users. Alternatively, each user could be equipped with a micro-computer to evaluate information transmitted by the warning system (such as preliminary event location and magnitude), and make decisions based on their local needs. The actual warning, in this case, becomes a local decision.

## Seismic Sensors and Data Acquisition

Earthquake warning sensor options range from simple seismic trip systems that only transmit data when specified level(s) of motion are exceeded, to the more sophisticated three-component, wide frequency-band, high dynamic range seismic sensors. The dynamic ranges of these seismic sensors extend from 6 db to more than 130 db.

**Level sensors**. These sensors trigger on the exceedance of specified levels of ground acceleration. They are reliable, use very little power, and are relatively inexpensive. After being triggered, the systems generally stay in the triggered state for a few tens of seconds after motions fall below and remain under the prescribed level. They then are reset and normal operation continues. Battery powered, three-component systems cost about $2,200. Data communications for these systems can be very inexpensive since only one bit data from each sensor is necessary.

**Force-balance accelerometers**. Force-balance accelerometers (FBAs) are the best available type of ground motion sensor that can monitor, on-scale, the levels of motion expected in the vicinity of the earthquake rupture process. Peak ground accelerations of up to 2.0g can be recorded. This type of sensor is a minimum requirement for a warning system that is to process continuous waveform data. Typical systems have a bandwidth of from DC to 50 Hz, and have a dynamic range of approximately 100 db. The peak ground acceleration is adjustable, but can exceed 2.0g. Triaxial FBAs cost approximately $2,600.

**Broad band strong motion seismometers.** These sensors are similar to the FBAs except that the acceleration response is from DC to 100 Hz, and the dynamic range is 150 db. Because of the extreme dynamic range of these systems, these sensors can be used to record relatively weak motions at the site for site calibration and operation testing purposes, thus increasing the reliability of the system. These systems cost approximately $9,800 for a triaxial set.

### Seismic Data Communication

The seismic data communication options are more diverse than any other aspect of the system. Seismic data can be transmitted in a variety of forms: (1) continuous three-component data that are telemetered in real time to a central processing computer; (2) three-component data that are transmitted only upon the detection of an earthquake; and (3) partial or summary data transmitted from a small processing unit in the vicinity of the sensors. The quantity of seismic data generated by a 50 station seismic network can easily exceed a quarter of a million bits per second. Therefore, any reliable alternatives to continuous data transmission rates would be desirable for cost savings. Locally stored data could be retrieved during slack times and used for system calibration and other research.

**Telephone and microwave systems.** In his evaluation of the Southern California seismograph array, Given (1987) considered the earthquake survivability of a variety of communications systems. He found that the weakest link in the southern California network is the telephone and microwave communications. The leased telephone lines are not subject to "call-saturation," a phenomenon commonly observed after any widely felt earthquake, because the lines are dedicated to the user and do not pass through the more vulnerable telephone line switching equipment. Nevertheless, Given was unable to derive a quantitative estimate for earthquake survivability because of the variety of systems that the phone companies use (both cables and microwave). For a complete survivability evaluation, the actual communications links used by the phone companies would have to be considered. Given did estimate that telephone telemetry could be significantly impaired in earthquakes of magnitude 7.5 and greater.

Survivability of microwave systems is also difficult to quantify because of the lack of earthquake experience data. Given estimated that an earthquake of magnitude 7 or less could significantly impair the State and Federal microwave systems by the misalignment of antennas and/or the upsetting of components caused by vibrations of the systems or structures.

**Direct VHF or UHF communication.** Direct transmission of seismic data via radio (VHF or UHF) is a relatively common practice, especially in the more rural areas of the state. Initial capital costs are relatively low (from $2,000 to $4,000 for each transmitter-receiver pair) and ongoing maintenance costs are small. Alignment of radio antennas (unlike that of microwave and satellite systems) is not especially critical. There are, however, several disadvantages. Transmission is limited to "line-of-sight" (about 80 km. maximum). Each transmitter/receiver pair must use a unique (within the local airspace) frequency. Frequency saturation in urban areas is making available frequencies scarce.

The frequency saturation problem can be minimized with a "packet" system. This system uses only one radio frequency. Information is transmitted in short, rapid bursts ("packets"). Communication is duplex; the recipient must send confirmation of perfect receipt of each packet. If there is interference and the intended recipient does not receive a perfect packet, the packet is resent. The information rate is slower than that possible with direct radio telecommunication. Baud rates range from 1200 to 9600 baud. But the effective baud rate is somewhat lower, because of the required receipt confirmation. System costs per site would be from $300 to $2,000 for the modem plus approximately $2,000 for a radio transceiver. Repeaters cost approximately $4,000. Approximately four repeaters would be required to assure coverage of the L.A. metropolitan area.

The packet system offers a possible alternative communication system for transmission of short bursts of summary data. Its primary drawback for warning would be a tendency for packets to collide (interference among several seismic stations attempting to communicate at the same time) during the very time that rapid data acquisition is required, during the earthquake. "Polling" of seismic stations by the central processor would eliminate these collisions, but the communication's overhead would be too great for an EWS. Nevertheless, the system could prove useful for a post-earthquake earthquake damage distribution evaluation system, for which neither the need for data nor the issuance of the warning to users is so immediate.

**Satellite–GOES**. The Geostationary Operational Environmental Satellite (GOES) communication system is used for a variety of purposes, including the transmission of tidal data for the Pacific tsunami warning hazard. The communication between the GOES system and the remote stations has four basic operational modes: (1) a self-timed mode, where each remote station transmits for one minute every three to four hours; (2) a random reporting mode, where the remote station turns on at random (but may not get through); (3) a combination of (1) & (2); and (4) an interrogate mode, where the platform responds within approximately five minutes of receiving a demand from a master station. The Pacific tsunami warning system uses the fourth mode. Currently, the GOES system transmits data at 100 baud, but future systems will be capable of 300 and 1200 bps. This communication system may be suitable for reporting exceedance of levels of motion for the simplest of EWS systems. The data from each station could consist of one word containing the identification code of the triggered sensor. Even with short communications bursts, however, the probability of two or more stations transmitting at the same time, interfering and preventing a warning from being issued is not insignificant. A GOES telemetry system would cost about $61,000 for a central data collection platform and $8,000 per sensor site for data collection and transmission platforms.

**Satellite–56 kilobaud**. Two types of wide-band satellite communication were considered. The first is a Time Domain Multiple Access (TDMA) approach on a dedicated 56 kilobaud satellite channel. This system could serve many of the high dynamic range sensors. Because the warning system does not require real-time communication of all earthquake data, one TDMA channel would be sufficient for warning purposes. This scheme is somewhat analogous to the trunk lines of a public telephone system. There is a finite capacity (or bandwidth) in the system, but on the average, only a fraction of the people who have telephones call at any given instant. The second type of satellite communication would use a number of these satellite channels to continuously transmit data.

The United States National Seismic Network (USNSN), a joint effort by the USGS and the Nuclear Regulatory Commission (NRC), plans to use the TDMA approach. The USNSN is planned to consist of approximately 150 seismic stations located in the contiguous U.S., Alaska, Hawaii, Puerto Rico, and the Virgin Islands. The installation of sensors and the communications system began in 1988, and is expected to be completed in six years. The purpose of this network is to detect and locate earthquakes of magnitude 2.5 and greater occurring within the network. This system will improve the seismic network coverage in the eastern U.S. and will provide on-scale data for the large earthquakes that would saturate the dynamic limits of both the sensors and the communications systems of current seismic networks.

The USNSN satellite communications system will have a total capacity of approximately 360 kilobits per second (kbps), with 56 kbps dedicated to the US network. Therefore, there is capacity for other seismic data. Each USNSN station will have a 1.8 meter satellite dish in continuous communication with the master earth station at the National Earthquake Information Center (NEIC) in Boulder, Colorado. If this system were used as the primary communication link between the seismic monitors of an EWS and its main processing computer, the data would be retransmitted to California on a dedicated EWS channel. Data transmission and retransmission would cause a total delay of approximately 1.5 seconds behind real-time.

The advantages of this type of system for the EWS data communications are the following: (1) the costs of the master earth station (approximately $1 million capital cost), required to collect data on the remote-station-to-Boulder transmission path, are already funded by the federal government; (2) the system is reliable (uptime > 99 percent and bit error rate of $10^{-12}$), and uses off-the-shelf components; (3) the system will be capable of transmitting high quality data in both burst and continuous modes (56 kbps); (4) the system will use Ku-band (12-18 GHz) and will not be sensitive to southern California weather; and (5) an EWS communications link would use only one channel of 56 kbps capacity with full duplex capability.

The potential problems with any high baud rate satellite communication system are: (1) satellite antennas require alignment to within a few degrees, thus, special testing and new engineering may be required to harden an installation against strong ground shaking; and (2) real-time delays in data transmission are about 2.5 seconds behind real time because of distances involved and and because of master earth station delays.

Dedicated 56 kbps channels cost about $14,000 per year. Hardware for satellite reception in California costs approximately $50,000 per channel.

A second type of system could consist of multiple 56 kbps channels. Each remote site would use all or a significant portion of the bandwidth of a channel for continuous data transmission. This system has all the advantages for early warning systems as the TDMA system described above, allows more control of the data because the transmission is continuous, and has only an approximate one second time delay to the data processing facility. This system requires earth station facilities (approximately $1 million) and leased satellite channels ($14,000/year each).

**Warning Transmission to User**

Any of the systems discussed above, in the section on seismic data communications, could be used for transmission of warning signals, regardless of simplicity or complexity, to the users. Users would have capital expenses of the receiving equipment, a computer for analysis and/or control and any special control subsystems. All of the options would have the same vulnerabilities as cited above. It may, however, be possible to use combinations of systems in a redundant communications system. Options for communication of earthquake warning include transmission to users over the following media: (1) satellite; (2) telephone and telegraph; (3) microwave; (4) radio and television; and (5) radio and television Cable networks.

Satellite transmission of direct digital seismic data from the sensors is the most expensive option for the EWS user, requiring approximately $50,000 in capital expense. Less expensive to the user are dedicated telephone and microwave systems, but these are judged to be less reliable. Dedicated radio transmission, perhaps using the packet concept, could be considerably cheaper, requiring only one master frequency and a perhaps relatively inexpensive radio receiver at the user's site.

One alternative to the direct warning center-to-user transmission, is the emergency notification concept of Emergency Broadcast Technologies Inc. (EBT). EBT has developed a 57 kHz radio subcarrier technology system, the Public Information and Notification System (PINS). PINS takes advantage of the existing broadcast infrastructure (FM radio stations, TV, and Cable stations) to provide a medium for transferring audio and digital information. Redundancy is built into the system by enabling many stations in an area to provide carrier signals. System performance and testing can be done end-to-end without the knowledge of, or interruption to, the user. "Live tests" can be performed with test messages to insure system integrity.

In an EWS application, the PINS system could be actuated by transmission of a warning signal (using one of the options discussed above) to one or more PINS "Gateway Stations" (PGS) in southern California. The PGS is a specially equipped FM radio station. The PGS can transmit one or more pre-programmed verbal or digital messages, or it can transmit digital data processed at the central computer site. Several PGS could be used to insure redundancy, and areas for warning could be selected by simply choosing a few specific PGS. FM, AM, TV, and Cable TV systems may be used.

There are several options for receiving the warning using this kind of system: (1) a special PINS pager, able to receive and store digital messages, and to translate onto an LCD display; (2) individual or group siren activation; (3) and emergency home receiver that, when activated, sounds an audio or visual alarm; (4) an emergency mobile receiver for busses and trains, and (5) an emergency industrial receiver that can activate PA systems, transfer emergency digital information to a local computer and/or activate automated systems. All of these notification systems continuously perform self-checking operations. Should a Gateway Station fail, these systems automatically search for other Gateway frequencies.

Advantages of a system like PINS are the built in redundancy and reliability, and the small capital costs to the end user. (Home receivers are currently priced at $40 each, industrial receivers at $300 each.) An additional advantage of PINS is its multi-hazard possibilities. Once the configuration is developed, the warning messages can originate from a variety of localities, and the messages can warn on a variety of hazards. Disadvantages of this system are the very large up-front costs, (approximately $2-5 million for coverage, both digital and voice, of the L.A. Basin) and the system overhead time to pass a message through the system (approximately 5 seconds).

**User Options**

Users could be given the option to receive raw data, certain semi-processed data or a simple warning signal, based on their facility needs and reliability requirements. Receipt of raw data would provide the most flexibility to the user, although at greatest cost, since the user would have to purchase the capability to receive and process all data. With this information, however, the user could customize the warning system to meet the facilities' specific needs regarding both shaking level for initiating action and system warning reliability.

The receipt of processed information, such as preliminary epicenter location, preliminary or current magnitude and measured distribution of strong ground shaking would provide nearly the same flexibility to the user, but without the great cost. The processed information could be transmitted by a relatively simple radio system, requiring only one frequency. A local processor, such as a PC, could receive and interpret the information, decide on the actions to be taken, if any, and initiate those actions.

Finally, receipt of a simple, or even a complex, warning signal from a central processor would require the least amount of processing on the part of the user. This warning signal could be one of several possible, for example,

1. a very simple two-state signal--there either is a warning in effect or there is not. The receiver could activate a siren, speaker or initiate actions to control processes at the user's facility. The user's only option is to accept or reject the warning.

2. a multiple-level signal, e.g., that there is a low, moderate or high probability of strong shaking (a yellow, orange and red alert). The levels could correspond to the reliability or confidence of the warning or to the expected level of shaking. The user may then

decide which level(s) is appropriate for his operations.

3. a signal containing some location information. In this case, the signal may have particular users or geographic areas coded into its signal. This would allow the warning signal to target those areas where strong shaking is expected, but not bother areas too far from the source to receive damaging levels of shaking. A radio transmitter with a limited range could be used to issue warnings over limited geographic areas. Note that the option of a multi-level warning and a geographically limited warning are not mutually exclusive. In fact, the combination of the two could, if developed properly, produce a very effective warning requiring a relatively inexpensive user's receiver. The PINS system discussed above could be used for this type of system.

### EWS Data Acquisition Systems

The various system configurations' costs cited in Chapters Four and Five were derived from this general discussion. Those configurations were derived assuming specific instrument options that may not perform all algorithms discussed in this appendix equally well, if at all. In this section, we discuss the initial design concepts for one of the configurations cited in Chapter Four and compare it with a more sophisticated system that would be required if the more sophisticated algorithms were employed for greater system reliability. We present these concepts to provide an idea of how the configuration options discussed above might be combined and to provide initial cost estimates for a particular system. Both of the systems presented assume that a 430 km segment of the San Andreas fault (from southern San Luis Obispo County to the Salton Sea) is to be instrumented with sufficient density to accomplish the desired task with a minimum of overhead time.

### System A

The first system contains 43 seismic sensor stations at 10 km intervals along the fault. This system is the same as System 1 in Table 6.4 in the body of this report. The sensors are standard force-balance accelerometers. Groups of 4 to 9 stations (depending on topography) transmit continuous digital data via direct VHF or UHF radio transmission to one of five (or more, if topography requires) processing hubs. Each of the hubs transmits partially processed, condensed seismic data, via separate 56 kilobaud satellite channels, to the central warning computer. The central warning computer issues warnings to users in the Los Angeles area via a system similar to the EBT PINS. An initial cost estimate for this system is as follows:

Capital Costs:

Field Instruments and installation $1,400,000

Central Site
$1,900,000

Annual Operation and
maintenance
$1,600,000

Cost estimates do not include the considerable software development requirements (probably several person-years) that will be required before the warning system becomes fully operational and reliable.

Note that an alternative configuration would be for the local computer to issue a warning based solely on the data from its 4 to 9 sensors. This could lessen the cost of the overall system by not requiring as sophisticated a central site, although each local computer may have to be somewhat more sophisticated. At the central site, system operation tests, algorithm and program development and data archiving would be carried out. If this option were chosen, some overlap among stations transmitting to adjacent local computers would be desirable.

**System B**

With the instrument options chosen in System A, the EWS could implement algorithms using peak ground acceleration (or velocity) or, possibly, the S-wave displacement pulse amplitude and width. If a more reliable estimate of an event's magnitude is required, the more sophisticated algorithms will have to be implemented. Data from the force-balance accelerometers may not have the bandwidth required to supply the information needed by these algorithms. Since these algorithms wait for fuller development of the earthquake (necessitating considerable system overhead time), close spacing of sensors is not required in this configuration. Here, then, we choose to place 14 broad-band, high dynamic range sensors at a spacing of 30 to 50 km along the fault. Again, a local computer gathers data from a limited number of stations. Because of distances involved, each local computer would be able to receive data from only 3 to 5 sensor stations. Data summaries are transmitted to a central computer that makes the warning decision and issues the warning. Preliminary cost estimates are:

Capital Costs:

Field Instruments and installation $1,900,000

Central Computer Site
$1,900,000

Annual Operation and
Maintenance:
$1,600,000

Again, these estimates do not include the rather extensive software development that will be necessary before the system could be fully operational and reliable.

As with the previous system, this system could (with a few added local processors and station overlap among local processors) issue warnings directly from the local computers, reducing the need of a central system to operation testing, algorithm and program development and data archiving.

A choice between these two systems depends on the amount of warning time and the accuracy/reliability required by the users. Extensive testing of existing data should be undertaken before any particular system is chosen.